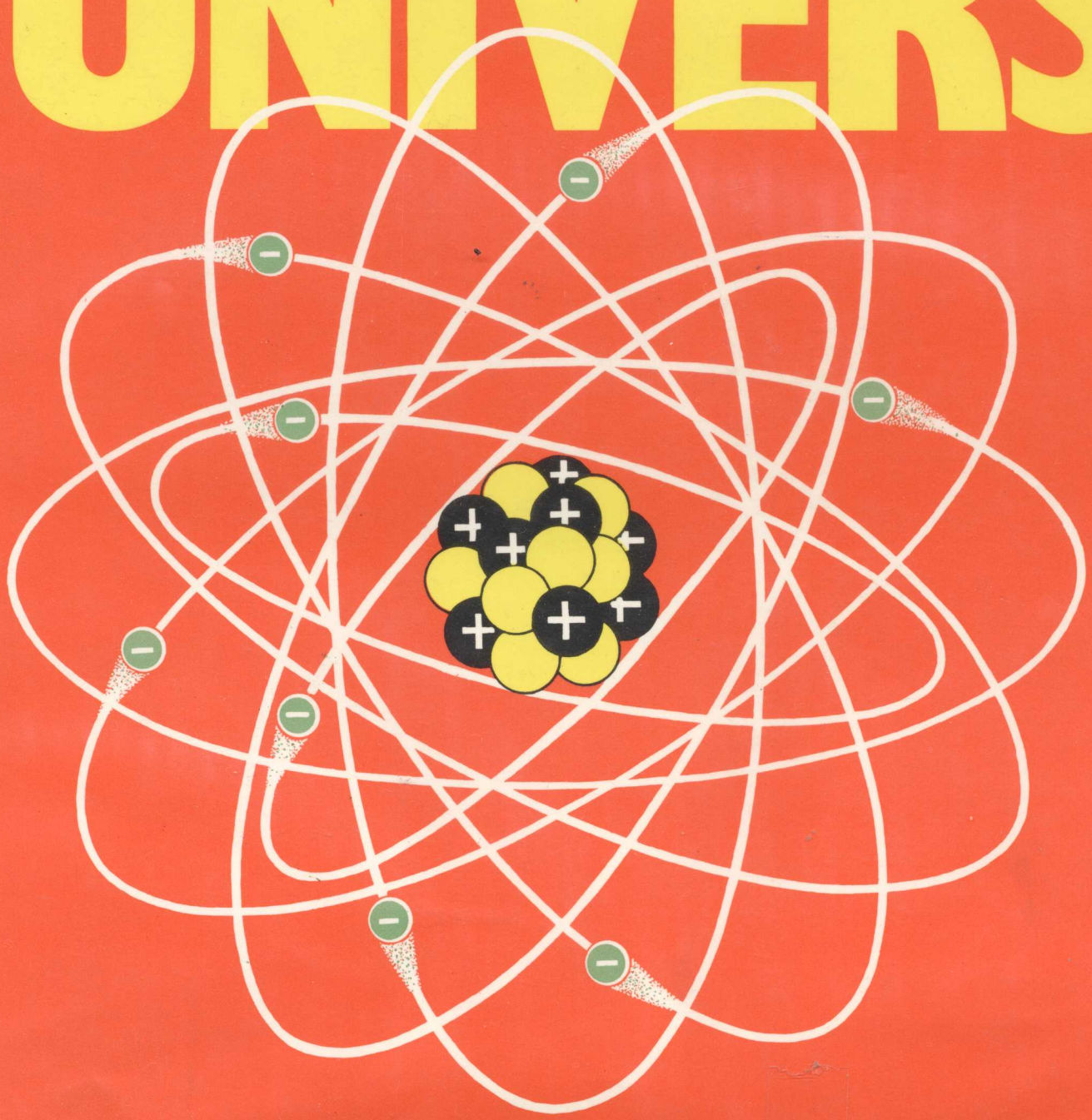
THE ATOMIC UNIVERSE

MIHAJLO VELIMIROVICH



The Atomic Universe is a vividly illustrated history and presentation of our knowledge of atomic physics and the nature of matter by a distinguished Yugoslav physicist.

The book visualizes mathematical and scientific information in an exciting and accessible way. It reveals, in terms that are easy to grasp, the world of the atom and the nucleus, and brings the story up to date with an account of the most recent forms of atomic power and energy. It covers such topics as the unity and composition of matter, ionization, fission, radiation, atomic weapons and gamma rays.

Taken all in all, the book is an important contribution to the understanding of atomic science for the layman, and will be particularly valuable in the school or college library.

This edition, translated from the Italian, includes scientific revision by Professor Ian Roxburgh and an experienced science teacher, R. J. Carlton.

THE ATOMIC UNIVERSE

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INTRODUCTION

This century has seen truly amazing advances in our scientific knowledge. The discoveries of science are more fascinating, more intriguing and more beautiful than anyone could have imagined. Throughout the last hundred years we have discovered the wonderful world of the atom and the nucleus, we have uncovered the laws which are obeyed by atoms and the particles of which they are made – laws which govern not only the atom but the whole universe, including man himself.

To know yourself you need to understand something of these laws and, in the following pages, this atlas opens up new worlds, new experiences and new self-knowledge. I hope that the reader will share the feeling of excitement and wonder that is experienced by the scientist as he learns of the complexity and intricacies of the atom. Perhaps the reader will see beyond – to the harmony and simplification in science where so many complex happenings, such as my writing this and your reading it, are all governed by the laws of atomic physics.

Professor IAN W. ROXBURGH
University of London

THE WORLDS OF CONTEMPORARY SCIENCE

We and the world in which we live are made of matter. Matter has many forms yet it is all related.

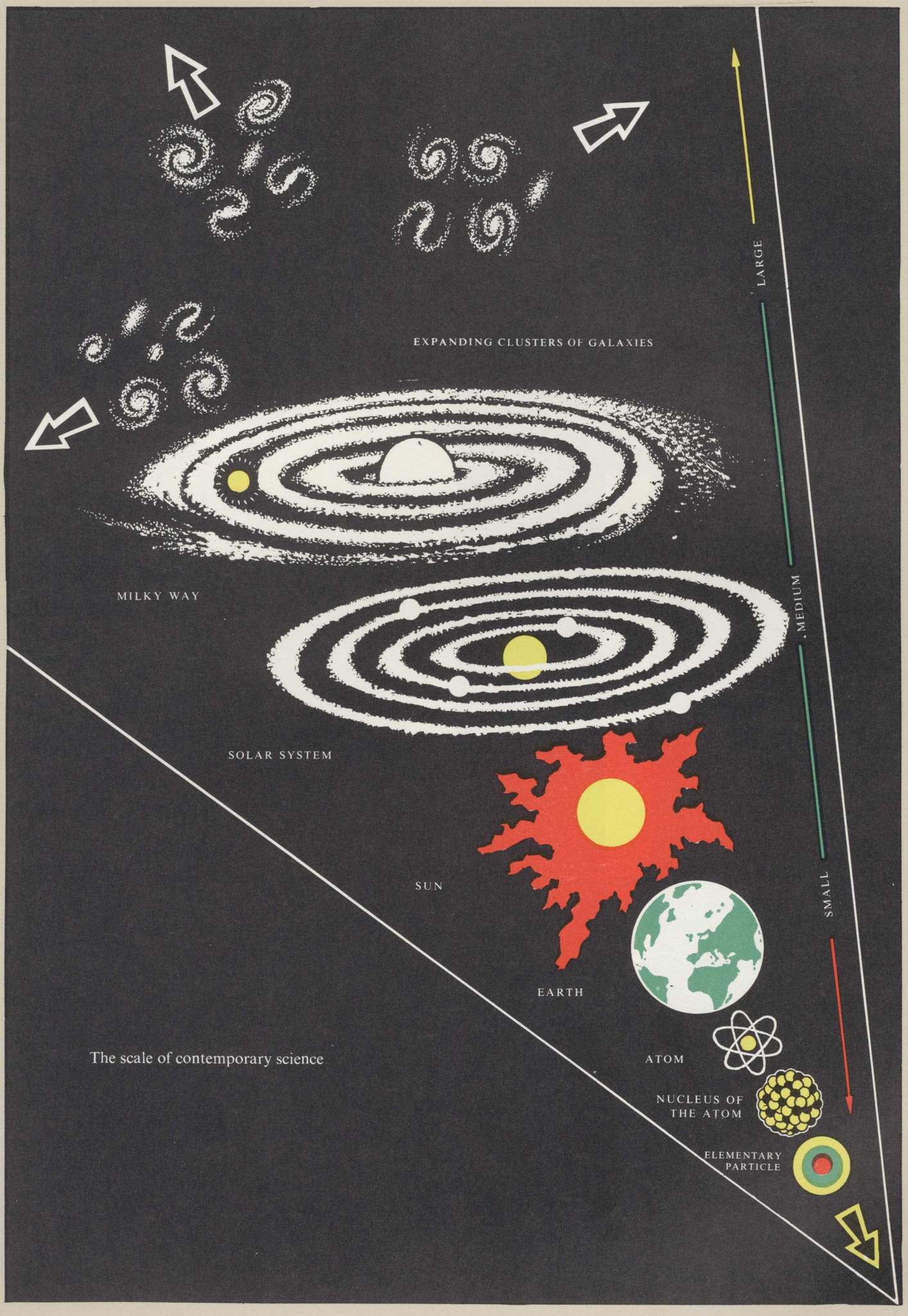
Space, with the clusters of galaxies receding from each other at enormous speeds, our galaxy with the Milky Way and our small solar system, the earth and the whole world of the atom and elementary particles are all different states, different complexities of the same kind of matter.

On the largest scale there is the universe, with clusters of galaxies. This is a world of vast dimensions, distances are measured in millions of millions of millions of kilometres. The duration of a process may be measured in millions of years and speeds in hundreds of thousands of kilometres per second. On this scale the whole universe is in a state of expansion.

On the intermediate scale we have the world of our normal experience, the world we are in daily contact with through our senses, which we see with our naked eye. It contains the solar system, the earth and all the life that proliferates on it. This is the state of matter nearest to our human experience and with which we are most familiar; and length is measured in centimetres or kilometres and time in seconds.

On the smallest scale there is the world of molecules, of atoms and elementary particles; a world man is just beginning to understand and explore. This is the world of the extremely small: length is measured in millionths or thousands of millionths of a centimetre while time is measured in millionths or thousands of millionths of a second.

Here science is at the very frontiers of its advance, and there are questions to be answered, even questions that have yet to be asked. But man will continue to search, to penetrate deeper into nature, revealing its secrets and discovering its laws.



The worlds of contemporary science

UNITY OF MATTER

Matter has many forms, comprising an enormous number of particles such as nuclei, atoms, crystals, etc., united in more or less stable systems; and matter is in continual motion.

The structure of the existing world presents two fundamental aspects: the form of bodies or particles, and the fields of physics – electromagnetic, gravitational, nuclear forces, etc.

The connecting mechanism between the wave and particle nature of matter has not yet been fully resolved by physics. The exact nature of the wave is also a controversial question, but it is a fact that all matter is corpuscular and simultaneously undulatory.

From this it follows that matter is of a dual nature, and physicists today are seeking to explain the reason for this duality.

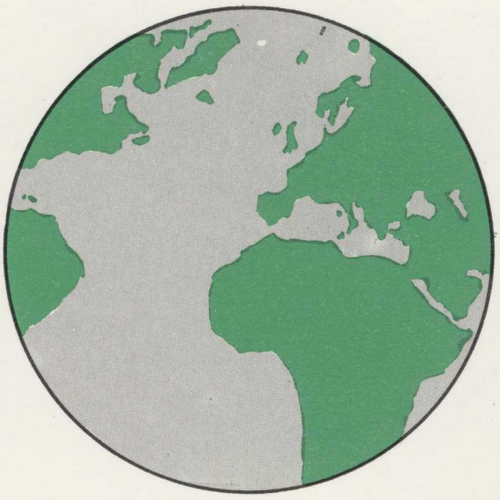
All matter in the known universe, from the gaseous clouds from which the solar system derives to the highest product of evolution, man, is composed of atoms and molecules.

Throughout the universe processes of chemical transformation are continuously taking place: the synthesizing of molecules and atoms, the formation of molecules from other molecules, and the dissociation of molecules.

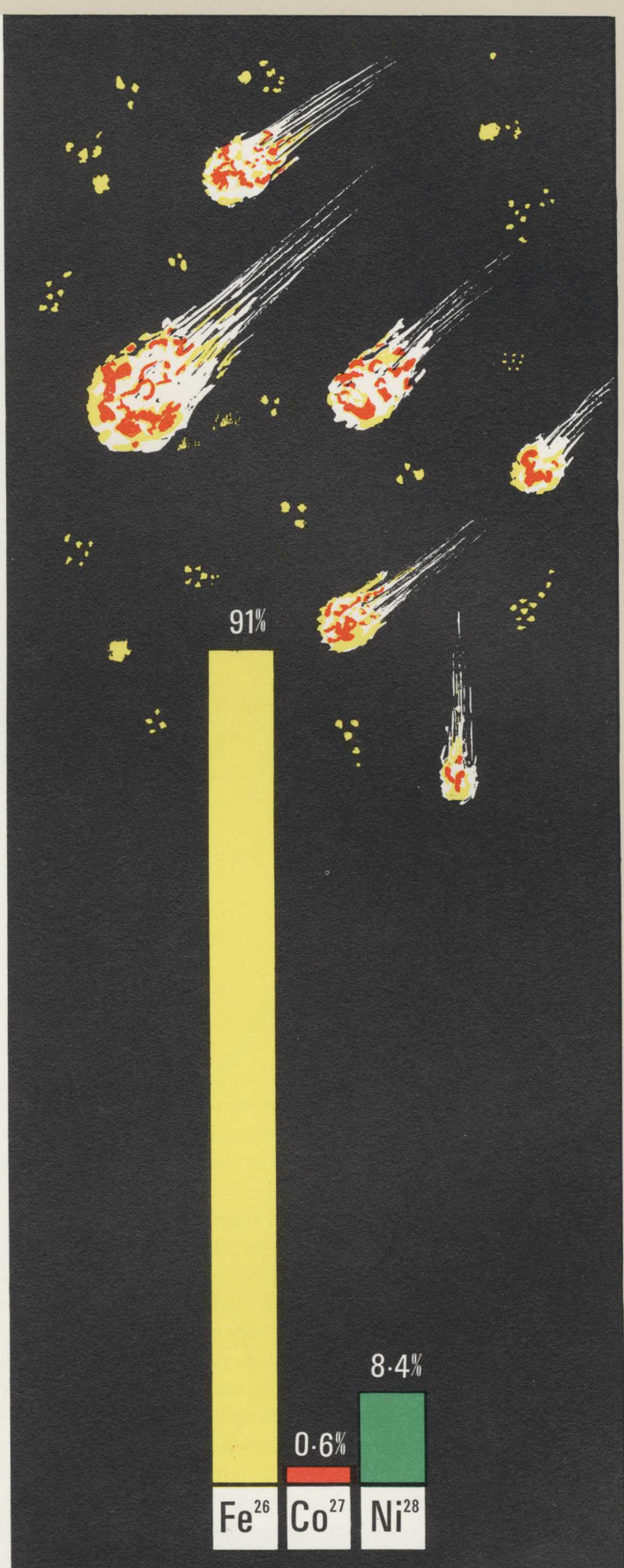
Besides these chemical changes, there are processes taking place in which elements are transformed, atoms of one type changing into atoms of another. Such changes are known as nuclear transmutations.

Matter is indestructible and is the subject of all natural phenomena and processes.

Matter is the unifying constituent of the world.



The unity of matter in the universe can be demonstrated with iron, cobalt and nickel. These elements exist on earth and throughout the universe. Moreover, their relative abundance in the meteorites which fall to earth is almost identical to their presence in the earth's crust. The absence of some elements in meteorites which are found in the earth's crust, such as aluminium, oxygen, can be explained by the fact that they evaporate at a relatively low temperature.



MATTER

What concept have we today of the structure of matter in its various forms?

Of the great number of elementary particles which we shall describe later, three particles are of prime importance in the structure of matter according to modern scientific ideas: the proton, electron and neutron.

Atoms cluster together to form molecules, while their surrounding orbital electrons arrange themselves in common patterns and their nuclei assume well-defined mutual positions.

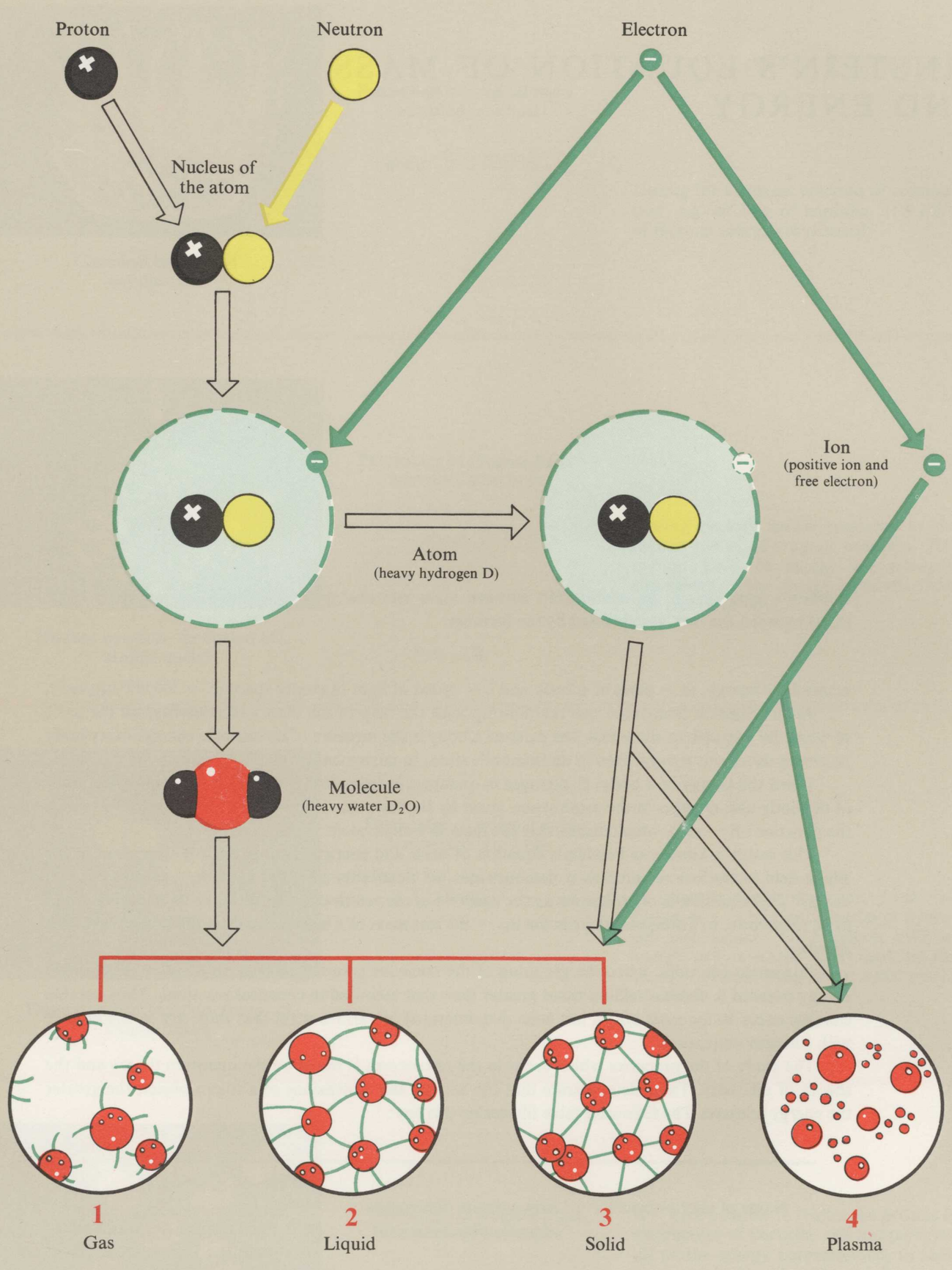
These clusters of matter change with an alteration of pressure or temperature. A given substance is in the solid state when the position and distance between the particles, atoms and molecules is fixed; in the liquid state only when their distance is more or less stable; in the gaseous state when the distance and position may vary, permitting the particles to move in all directions; in the plasma state when the particles, that is, the atoms, become ionized.

When a substance is in the gaseous state, the molecules are situated at a relatively greater distance from each other, and their mutual force of attraction is small; thus gas diffuses through an empty space.

The arrangement of molecules in the liquid state is almost the same as in the gaseous state, except that the molecules are closer together and interact with one another.

The solid state of a substance is almost always characterized by the fact that its particles are arranged geometrically, and this leads to most solid substances having crystalline structures. Only in certain cases are these crystalline networks formed of molecules; more often they are formed of simple atoms, that is by positive and negative ions.

Matter in a highly ionized state is known as plasma or the fourth state (after the gaseous, liquid and solid states). In this state a substance is formed of 'naked' atomic nuclei and of free electrons which are in thermal motion. Plasma is a strong conductor of electricity.



When a substance is in the gaseous state (1) the particles move freely, changing distance and position amongst themselves. In the liquid state (2) their movement is limited by the fact that the distance must be more or less fixed; while in the solid state (3) the particles can only rotate and vibrate around a point of equilibrium, maintaining a fixed distance and position. At high temperatures (several million degrees or more) the substance becomes a plasma (4). The system is entirely ionized, that is, formed of naked atomic nuclei with a positive charge and of electrons with negative charges in thermal motion.

EINSTEIN'S EQUATION OF MASS AND ENERGY

Einstein's equation on the relationship between mass and energy demonstrates that an equivalence exists between the two, as expressed by the formula:

$$E = mc^2$$

where E = energy, m = mass of a body and c = speed of light in empty space (c = 300,000 km/sec.).

Albert Einstein discovered this relationship with the help of his theory of relativity, on the basis of which he was able to show that 'the mass of a body is the measure of its intrinsic energy; every body possesses enormous energy, even in an immobile state; in movement its mass increases'.

When the energy of a body, E, changes in quantity, independent of the form it assumes, the mass of the body also changes in the same sense, given by the formula: E/c^2. Thus it is possible to establish the equation: $E = mc^2$, which means that the mass m is equivalent to the energy E.

This result is known as Einstein's equation of mass and energy and is extremely important in the whole field of nuclear research as it demonstrates the possibility of releasing enormous quantities of energy. This equation is often known as the *equation of the relativity of mass*, while the mass m is said to be *relativistic*, to distinguish it from the m_0 = the rest mass of a body in an immobile state or at slow speeds.

In nuclear reactions, when the grouping of the nucleons is modified within the atomic nuclei, the energy released is about a million times greater than that recorded in chemical reactions. Thus notable changes occur in the mass and it has been demonstrated in various ways that these are in accordance with Einstein's equation.

The study of the processes which occur in the microcosm is based on the quantum theory and the theory of relativity. These demonstrate that the smaller the dimensions of a micro-object, the greater the energy released. The following table illustrates this law:

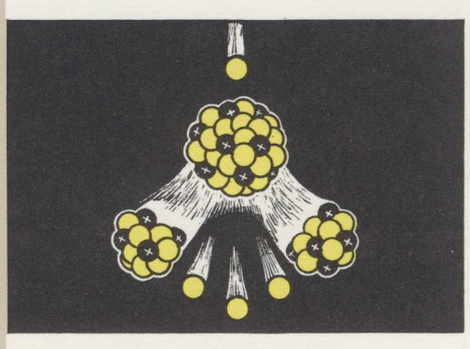
Name of micro-objects	Approximate dimensions of micro-objects (in cm)	Energy developed in the processes taking place in micro-objects (size order in eV)
Atom	10^{-8}	1
Nucleus	10^{-12}	10^6
Nucleon	10^{-13}	10^9

Chemical reaction of combustion

Percentage of original mass converted into heat

about **0·0000001%**

During the chemical reaction of combustion, e.g. of 1 kg of naphtha, 11·6 kWh of thermal energy are released.

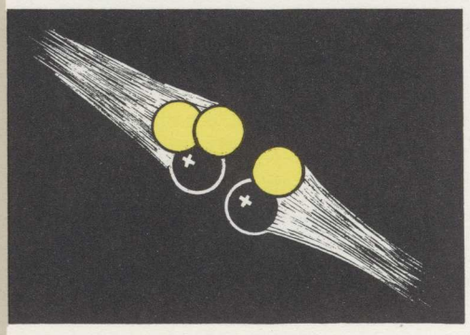


Nuclear reaction, the fission of atomic nuclei

Percentage of original mass converted into heat

about **0·1%**

During nuclear fission reactions in the atomic nuclei of 1 kg of uranium, 22·9 million kWh of energy are released, equivalent to the energy obtained from 300 trucks of coal.

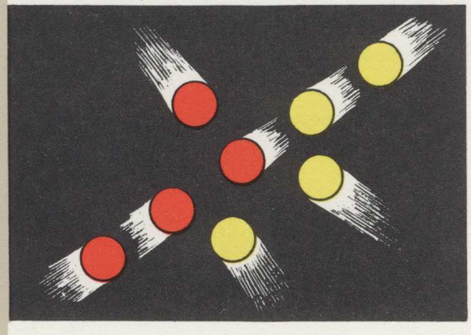


Thermonuclear reaction, fusion of atomic nuclei

Percentage of original mass converted into heat

about **1%**

In thermonuclear reactions, from the fusion of 1 kg of atomic nuclei of hydrogen into helium, 177·5 million kWh of energy are released, equivalent to the energy obtained from about 3,000 trucks of coal.



Process of destruction of particles and antiparticles

Percentage of original mass converted into heat

100%

If it were possible to realize the process of destruction of particles and antiparticles, all of the energy corresponding to their mass would be released, and from 1 kg of mass, we should obtain 25,000 million kWh of energy, equivalent to about 300,000 trucks of coal.

PERIODIC GROUPING OF THE ELEMENTS

The periodic grouping of elements is the classification of the chemical elements according to the periodic laws of the interdependence between the chemical and physical properties of the elements and their relative atomic masses. The discovery of the laws of periodicity and the first classification of the elements were made by D. I. Mendeleev.

The chemical elements are ordered in seven horizontal *periods* of progressively increasing mass, in such a way that related elements form eight vertical groups. Hence the periodicity of the chemical and physical properties with the increase in relative atomic mass is clearly apparent. Later on when the so-called inert gases were discovered, a ninth group, the zero, was added to the periodic system.

The periodic table contributed greatly to the discovery of further unknown elements and the calculation of their chemical and physical properties.

To date, 103 natural and artificial elements have been discovered, and this figure does not include their hundreds of isotopes.

The periodic table of elements is formed of horizontal progressions known as periods, which contain 2, 8, 8, 18, 18, 32 and 17 elements.

In each period we find a characteristic behaviour in the change of chemical and physical properties from one element to another. In some cases this behaviour is very pronounced, while in others it is relatively moderate. This depends on the structure of the atom in the respective elements.

The vertical columns into which the table is divided are called *groups*, some of which contain subgroups. In each subgroup the elements have analogous properties.

When the inert gases were discovered, it was found that they form a group also to be found among those already in existence, and so to avoid a re-numbering, they were marked with a 0.

In group III of the 6th period, instead of one element there are 14 with atomic numbers from 57 to 71. These elements are arranged one by one underneath the principle table and are called *lanthanides* (from Lanthanum) but are better known by the name of *rare earths*.

Beginning with Actinium whose atomic number is 89, there follows a series of *actinides* also arranged one by one under the principle table. In this group are the *transuranium elements*, chemically similar, but created artificially and nonexistent in nature.

The table also indicates the atomic structure of each element, that is, its *atomic number*, *relative atomic mass*, and the *number of electrons* in each orbit.

PERIODIC TABLE OF THE ELEMENTS

GROUPS OF ELEMENTS

Periods	Series	Elect. shells	I	II	III	IV	V	VI	VII	VIII			0
1	I	K	**H** 1 HYDROGEN 1·0080 1										**He** 2 HELIUM 4·0026 2
2	II	L K	**Li** 3 LITHIUM 6·939 1 2	**Be** 4 BERYLLIUM 9·0122 2 2	**B** 5 BORON 10·811 3 2	**C** 6 CARBON 12·0111 4 2	**N** 7 NITROGEN 14·0067 5 2	**O** 8 OXYGEN 15·9994 6 2	**F** 9 FLUORINE 18·9984 7 2				**Ne** 10 NEON 20·183 8 2
3	III	M L K	**Na** 11 SODIUM 22·9898 1 8 2	**Mg** 12 MAGNESIUM 24·312 2 8 2	**Al** 13 ALUMINIUM 26·9815 3 8 2	**Si** 14 SILICON 28·086 4 8 2	**P** 15 PHOSPHORUS 30·9738 5 8 2	**S** 16 SULPHUR 32·064 6 8 2	**Cl** 17 CHLORINE 35·453 7 8 2				**Ar** 18 ARGON 39·948 8 8 2
4	IV	N M L K	**K** 19 POTASSIUM 39·102 1 8 8 2	**Ca** 20 CALCIUM 40·08 2 8 8 2	**Sc** 21 SCANDIUM 44·956 2 9 8 2	**Ti** 22 TITANIUM 47·90 2 10 8 2	**V** 23 VANADIUM 50·942 2 11 8 2	**Cr** 24 CHROMIUM 51·996 1 13 8 2	**Mn** 25 MANGANESE 54·9380 2 13 8 2	**Fe** 26 IRON 55·847 2 14 8 2	**Co** 27 COBALT 58·9332 2 15 8 2	**Ni** 28 NICKEL 58·71 2 16 8 2	
	V	N M L K	**Cu** 29 COPPER 63·54 1 18 8 2	**Zn** 30 ZINC 65·37 2 18 8 2	**Ga** 31 GALLIUM 69·72 3 18 8 2	**Ge** 32 GERMANIUM 72·59 4 18 8 2	**As** 33 ARSENIC 74·9216 5 18 8 2	**Se** 34 SELENIUM 78·96 6 18 8 2	**Br** 35 BROMINE 79·909 7 18 8 2				**Kr** 36 KRYPTON 83·80 8 18 8 2
5	VI	O N M L K	**Rb** 37 RUBIDIUM 85·47 1 8 18 8 2	**Sr** 38 STRONTIUM 87·62 2 8 18 8 2	**Y** 39 YTTRIUM 88·905 2 9 18 8 2	**Zr** 40 ZIRCONIUM 91·22 2 10 18 8 2	**Nb** 41 NIOBIUM 92·906 1 12 18 8 2	**Mo** 42 MOLYBDENUM 95·94 1 13 18 8 2	**Tc** 43 TECHNETIUM (97) 2 13 18 8 2	**Ru** 44 RUTHENIUM 101·07 1 15 18 8 2	**Rh** 45 RHODIUM 102·05 1 16 18 8 2	**Pd** 46 PALLADIUM 106·4 0 18 18 8 2	
	VII	O N M L K	**Ag** 47 SILVER 107·870 1 18 18 8 2	**Cd** 48 CADMIUM 112·40 2 18 18 8 2	**In** 49 INDIUM 114·82 3 18 18 8 2	**Sn** 50 TIN 118·69 4 18 18 8 2	**Sb** 51 ANTIMONY 121·75 5 18 18 8 2	**Te** 52 TELLURIUM 127·60 6 18 18 8 2	**I** 53 IODINE 126·044 7 18 18 8 2				**Xe** 54 XENON 131·30 8 18 18 8 2
6	VIII	P O N M L K	**Cs** 55 CESIUM 132·05 1 8 18 18 8 2	**Ba** 56 BARIUM 137·34 2 8 18 18 8 2	**La** *57 LANTHANUM 138·91 2 9 18 18 8 2	**Hf** 72 HAFNIUM 178·49 2 10 32 18 8 2	**Ta** 73 TANTALUM 180·48 2 11 32 18 8 2	**W** 74 TUNGSTEN 183·85 2 12 32 18 8 2	**Re** 75 RHENIUM 186·22 2 13 32 18 8 2	**Os** 76 OSMIUM 190·2 2 14 32 18 8 2	**Ir** 77 IRIDIUM 192·2 0 17 32 18 8 2	**Pt** 78 PLATINUM 195·09 1 17 32 18 8 2	
	IX	P O N M L K	**Au** 79 GOLD 196·967 1 18 32 18 8 2	**Hg** 80 MERCURY 200·59 2 18 32 18 8 2	**Tl** 81 THALLIUM 204·37 3 18 32 18 8 2	**Pb** 82 LEAD 207·19 4 18 32 18 8 2	**Bi** 83 BISMUTH 208·980 5 18 32 18 8 2	**Po** 84 POLONIUM (209) 6 18 32 18 8 2	**At** 85 ASTATINE (210) 7 18 32 18 8 2				**Rn** 86 RADON (222) 8 18 32 18 8 2
7	X	Q P O N M L K	**Fr** 87 FRANCIUM (223) 1 8 18 32 18 8 2	**Ra** 88 RADIUM (226) 2 8 18 32 18 8 2	**Ac** **89 ACTINIUM (227) 2 9 18 32 18 8 2	(104)	(105)	(106)	(107)	(108)	(109)	(110)	
			(111)	(112)	(113)	(114)	(115)	(116)	(117)	(118)			

LANTHANIDES

P O N M L K	**Ce** 58 2 8 20 18 8 2 CERIUM 140·12	**Pr** 59 2 8 21 18 8 2 PRASEODYMIUM 140·907	**Nd** 60 2 8 22 18 8 2 NEODYMIUM 144·24	**Pm** 61 2 8 23 18 8 2 PROMETHIUM (145)	**Sm** 62 2 8 24 18 8 2 SAMARIUM 150·35	**Eu** 63 2 8 25 18 8 2 EUROPIUM 151·96	**Gd** 64 2 9 25 18 8 2 GADOLINIUM 157·25
P O N M L K	**Tb** 65 2 9 26 18 8 2 TERBIUM 158·924	**Dy** 66 2 9 27 18 8 2 DYSPROSIUM 162·50	**Ho** 67 2 9 28 18 8 2 HOLMIUM 164·930	**Er** 68 2 9 29 18 8 2 ERBIUM 167·26	**Tu** 69 2 9 30 18 8 2 THULIUM 168·934	**Yb** 70 2 9 31 18 8 2 YTTERBIUM 173·04	**Lu** 71 2 9 32 18 8 2 LUTETIUM 174·97

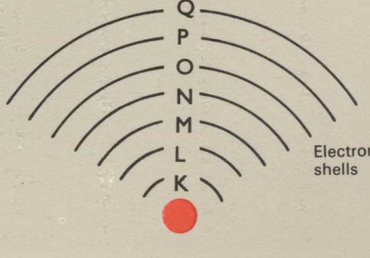
ACTINIDES

Q P O N M L K	**Th** 90 2 10 18 32 18 8 2 THORIUM 232·038	**Pa** 91 2 9 20 32 18 8 2 PROTACTINIUM (231)	**U** 92 2 9 21 32 18 8 2 URANIUM 238·03	**Np** 93 2 8 23 32 18 8 2 NEPTUNIUM (237)	**Pu** 94 2 8 24 32 18 8 2 PLUTONIUM (244)	**Am** 95 2 8 25 32 18 8 2 AMERICIUM (243)	**Cm** 96 2 9 25 32 18 8 2 CURIUM (247)
Q P O N M L K	**Bk** 97 2 8 27 32 18 8 2 BERKELIUM (247)	**Cf** 98 2 8 28 32 18 8 2 CALIFORNIUM (251)	**Es** 99 2 8 29 32 18 8 2 EINSTEINIUM (254)	**Fm** 100 2 8 30 32 18 8 2 FERMIUM (253)	**Md** 101 2 8 31 32 18 8 2 MENDELEVIUM (256)	**No** 102 2 8 32 32 18 8 2 NOBELIUM (253)	**Lw** 103 2 9 32 32 18 8 2 LAWRENCIUM (257)

Q P O N M L K (Electron shells)

U — 92 (Atomic number) — URANIUM (Name of the element) — 238·03 (Atomic mass)

2 9 21 32 18 8 2 (No. of electrons per shell)



Periodic table of the elements

THE ATOM

The first ideas about the atom were formulated by the Greek philosophers twenty-five centuries ago, yet true atomic science, based on experimental facts, is relatively recent: it was only at the start of the nineteenth century that scientists introduced atoms into modern chemistry. However, their concept did not differ substantially from that of the Greeks, since they believed atoms to be the ultimate, indivisible particles of matter.

The discovery of radioactivity was of prime importance for a knowledge of the internal structure of the atom. In 1896 H. Becquerel observed that uranium minerals, without any external excitation, emit very penetrating radiations having much smaller wavelengths than those of X-rays.

This discovery was of particular interest to Marie and Pierre Curie, who wanted to find out the origin and nature of these rays, and to establish whether this was a property of uranium alone, or of other elements too, such as polonium and radium.

When it was established that radioactive substances emit alpha, beta and gamma rays the question arose as to why the atom possessed so much energy (1 g of radium emits 37,000,000,000 particles a second).

Albert Einstein provided the answer in 1905. The conclusion derived from his theory of relativity, was that a close relationship exists between mass and energy, so that 1 g of any substance whatever would produce 25,000,000 kWh if it were all transformed into energy.

These discoveries encouraged scientists throughout the world to study the structure of the atom more closely. E. Rutherford and N. Bohr are the first names to note: they ascertained that the atom has a structure of its own and is formed of a nucleus, in which almost its entire mass is concentrated, and a surrounding cloud of electrons which gyrate in fixed orbits.

In 1919 the artificial transformation of one element into another (transmutation) was discovered: when nitrogen is bombarded with alpha particles it is transformed into oxygen.

In 1932 I. Chadwick discovered the neutron, a neutral particle forming part of all atomic nuclei with the exception of hydrogen. As it is uncharged the nucleus cannot exert a repulsive force on the nucleus, and so it can easily penetrate it.

In the same year W. Heisenberg and D. Ivanenko independently reached the conclusion that the nucleus of the atom is composed of two types of particles: positively charged protons and uncharged neutrons.

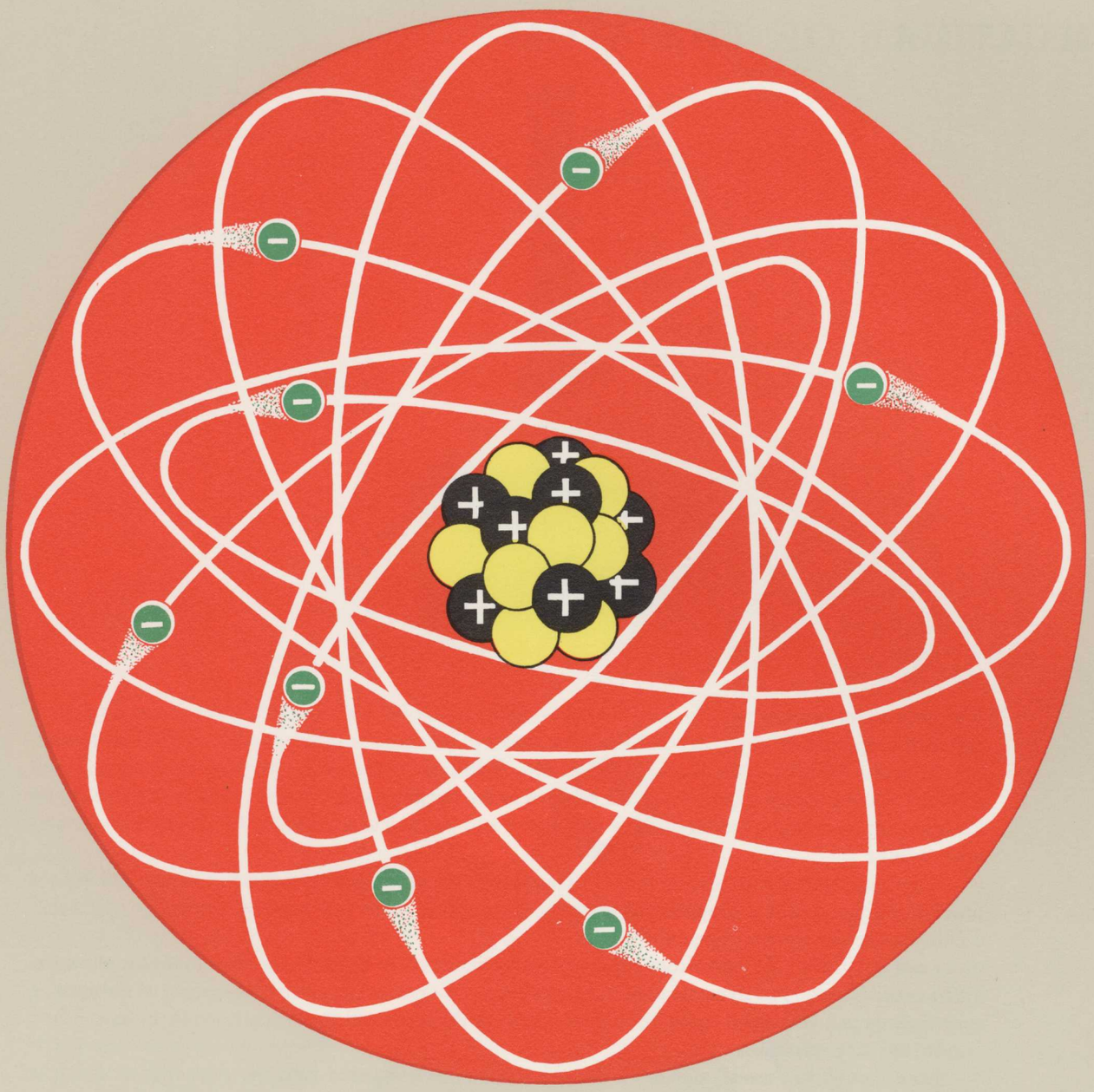
By bombarding uranium with slow neutrons, scientists discovered a new and very important phenomenon: the fission of the uranium nucleus. This phenomenon is accompanied by the release of enormous energy. An important role in this discovery was played by Irene Curie, daughter of Marie and Pierre Curie, and also by the scientist P. Savic.

In America in 1942 Enrico Fermi built an apparatus for controlling the release of nuclear energy: the nuclear reactor.

A few years later, in 1945, the first atomic bomb was exploded. In 1954 the first atomic power station was opened in the Soviet Union.

Beside the fission of heavy atomic nuclei, the opposite process was discovered, that is, the fusion of light atomic nuclei, analogous to that which takes place in the sun and stars.

Nuclear energy is becoming one of the most important factors for the present and future progress of humanity.



Structure of the atom

The atom is composed of a nucleus and a surrounding electron cloud. The nucleus is the internal, central part of the atom and is composed of protons (positively charged particles) and neutrons (uncharged particles) very closely linked together. Almost the entire mass of the atom is concentrated in the nucleus. The charge is positive. The electron cloud is composed of negatively charged electrons which gyrate around the nucleus at enormous speed. In the normal state, the atom is electrically neutral, because the number of orbiting electrons corresponds to the number of protons in the nucleus.

Protons Neutrons Electrons

STRUCTURE OF THE ATOM

The atom is the smallest particle of a chemical element which can exist by itself while conserving all its chemical properties. In combination with other atoms of the same or different types, it gives molecules.

Although the atom is the smallest particle of a chemical element, it has, nevertheless, a complicated structure and represents a large system in relation to the particles which form it. (The measurements of the atom are one hundred millionth of a centimetre and its nucleus is from ten to a hundred thousand times smaller.)

According to the early model of J. J. Thompson, the atom was conceived as a tiny ball with a positive charge, spread throughout its volume, while inside there was negative electricity (electrons) oscillating around a point of equilibrium.

Later on, in 1911, E. Rutherford suggested a new model of the atom on the basis of his experiments, the so-called *planetary* or dynamic model. According to this model, the positive electricity of the atom is concentrated in a very small space, the nucleus, and the electrons which envelop it gyrate in fixed orbits at relatively large distances.

Even though this model signifies a decisive advance as compared with the preceding model, it is still imperfect. First of all, it does not supply an answer to the question of the atom's stability, and second, it does not clarify the nature of the luminous radiation which it emits.

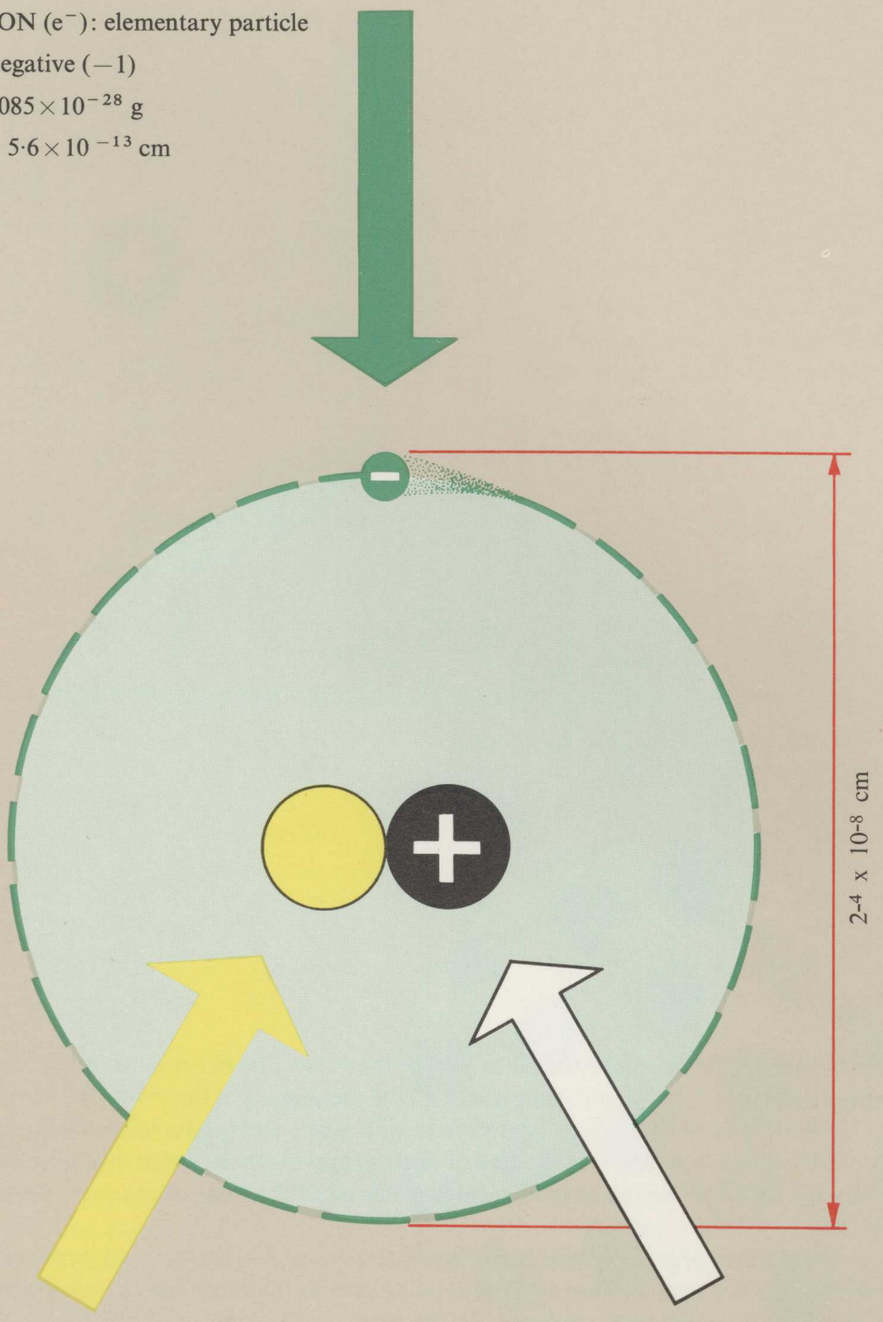
The dynamic model of the atom was perfected in 1913 by Niels Bohr with the hypothesis of stationary states: in such a state there is no emission or absorption of electromagnetic waves (light), emission or absorption occurring only during the passage of an atom from a stationary state to a state of different energy. On the basis of this model, the fundamental measurements were calculated for the movement of the electrons in a hydrogen atom, the speed of the electron, the atomic radius and the energy of ionization in the atom.

It was shown that atoms do not assume stationary states of arbitrary energy, but that discrete states of energy exist in them. The electrons rotate in orbit at different distances from the nucleus and a fixed quantity of energy corresponds to each orbit. The passage of the atom from one state to the other is explained by the electron jumping from one orbit to another.

In a normal state, the atom is electrically neutral, because the number of orbiting electrons is equal to the number of protons in the nucleus. The protons in the nucleus and the electrons of the external orbits attract one another. This electrostatic attraction compels the electrons to remain near the nucleus and maintains the stability of the atom.

In certain conditions atoms may expel or receive electrons and so become electrified positively or negatively, thus becoming ions.

ELECTRON (e^-): elementary particle
Charge: negative (−1)
Mass: $9{\cdot}1085 \times 10^{-28}$ g
Diameter: $5{\cdot}6 \times 10^{-13}$ cm



NEUTRON (n): elementary particle
Charge: nil (0)
Mass: $1{\cdot}6747 \times 10^{-24}$ g
Diameter: approximately $1{\cdot}5 \times 10^{-13}$ cm

PROTON (p): elementary particle
Charge: positive (+1)
Mass: $1{\cdot}6724 \times 10^{-24}$ g
Diameter: approximately $1{\cdot}6 \times 10^{-13}$ cm

Diagram of the structure of heavy hydrogen

THE NUCLEUS OF THE ATOM

The nucleus is the internal constituent part of the atom. The dimensions of the nucleus are extraordinarily small (10^{-13}–10^{-12} cm) compared with the dimensions of the atom (10^{-8} cm).

The density of the nucleus is extraordinarily great: more than 100,000,000 tons/cm^3. The nucleus is positively charged, and is composed of protons and neutrons which thus take the name of nucleons. They are so tightly linked as to concentrate almost all the mass of the atom (over 99 per cent) in the nucleus.

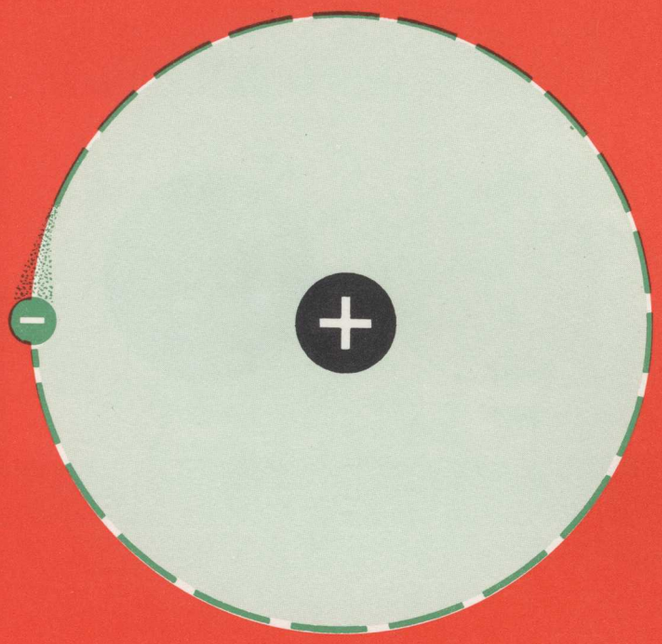
The number of protons determines the electric charge Z of the nucleus (atomic number in the periodic table), while the total number of protons and neutrons (nucleons) more or less determines its mass (or relative atomic mass) and is indicated by the letter A. The number of neutrons in the nucleus is almost equal to, or slightly greater than, the number of protons, especially in the elements with a high Z value.

As well as A and Z, each nucleus is characterized by the binding energy, rest mass, radius, spin (the spin is the moment of the quantity of motion of the nucleus) and by magnetic and electric moments.

The mass of the nucleus, measured with the spectograph and expressed in units of mass, differs from the sum of the masses of constituent nucleons, the so-called mass defect.

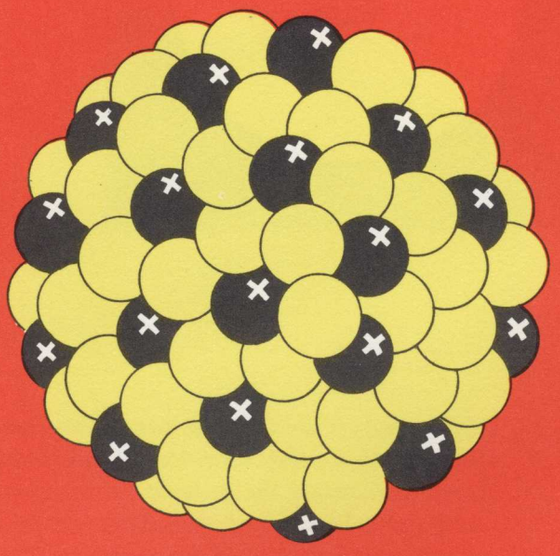
Besides the force of repulsion between protons, there is also a force of attraction between the nucleons, known as the nuclear force. Owing to the great intensity of the nuclear forces, the bonding energy of the nucleus reaches tens and hundreds of millions of eV (1 electronvolt or eV $= 1{\cdot}60 \times 10^{-19}$ joules).

The structure of the nucleus is very complex. Of the nature of nuclear forces we know only that they are extremely intense at small distances and decrease rapidly at greater distances. The atomic nucleus is not only the origin of nuclear energy; from its transformation we obtain the transformation of the elements, that is, nuclear transmutation.



The atom of hydrogen is the lightest of the atoms. Its nucleus is the simplest and is composed of a single nuclear particle – the proton – around which one electron orbits.

The nucleus of the uranium atom, that is of the heaviest element found in nature, is composed of 92 protons and 146 neutrons (its relative atomic mass – A – is 238, and corresponds to the number of nucleons in the nucleus).



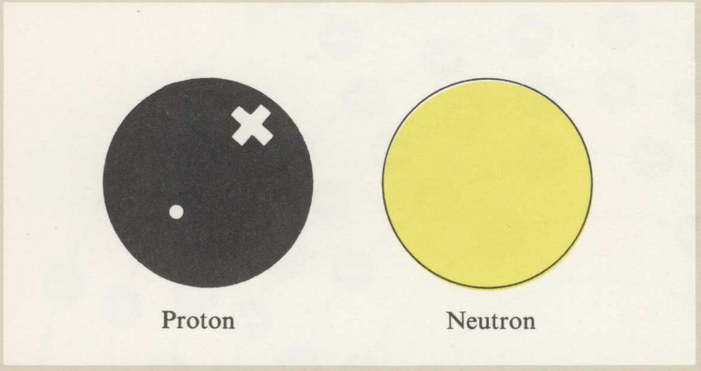
A = relative atomic mass, indicating the total number of nucleons – protons and neutrons – in the nucleus of the atom (A = Z+N)
Z = atomic number, indicating the number of protons in the nucleus of the atom (Z = A−N)
N = number of neutrons in the nucleus of the atom (N = A−Z)

NUCLEONS

Until recently it was thought that the nucleons – protons and neutrons – were small, compact 'balls'. Instead, the latest discoveries have shown that the so-called elementary nuclear particles have a structure of their own; that is, the nucleons are also compound structures. What we called the nucleon up to now, was in reality its idealized appearance. Today we believe that the nucleon is composed of a central core and a surrounding cloud of mesons which always accompanies the nucleon; this means that the nucleon has its own structure conditioned by the properties of the various particles – it has been shown that the properties and structure of an elementary particle depend on the properties of other particles.

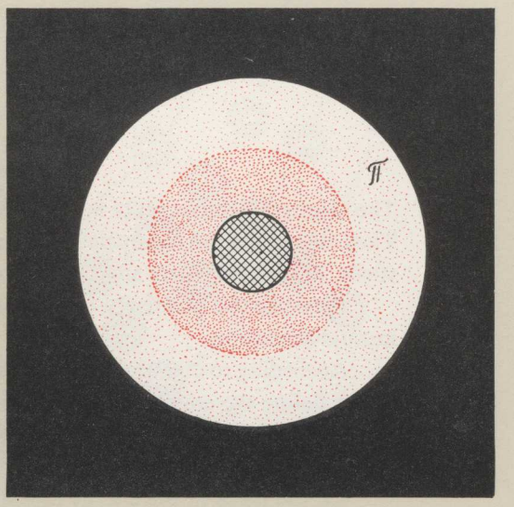
In experimental fields the term nucleon is used to indicate the mesonic cloud and its centre, a type of core, which was previously referred to generally as nucleon. In the nucleon processes are taking place continually, and so its various 'appearances' change with such speed that it is impossible to follow them.

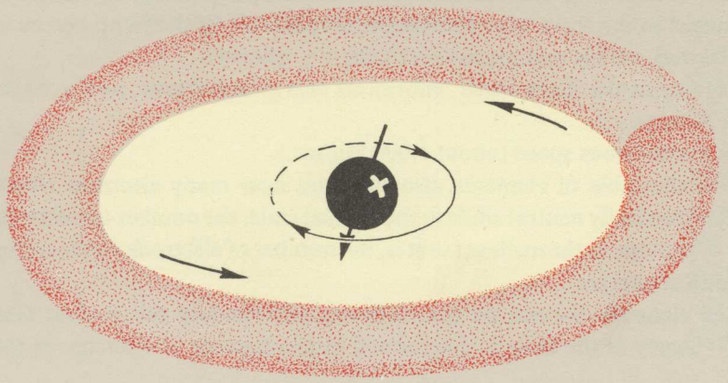
Except for the periphery of which a reasonably good theoretical description exists, the external part of the nucleon which is represented by the mesonic cloud has not yet been studied sufficiently. Together with the problem of the structure of nucleons there is a series of new and interesting problems in the physics of elementary particles, and until we understand the structure of the nucleon we will not understand the force between different nucleons.



Nucleons is the collective name for the particles which constitute the nucleus of the atom: neutrons and protons. In the theory of the atomic nucleus, the proton and neutron are often considered as two different states of a single particle: the nucleon.

According to some modern hypotheses the nucleon may be thought of as follows: at the centre a type of core (radius approximately 10^{-14} cm) around which there is the pi-mesonic atmosphere of the nucleon (radius approximately 10^{-13} cm) and the pi-mesonic stratosphere (radius approximately greater than 10^{-13} cm).





According to a recent hypothesis, the proton is similar to the planet Saturn: during a period of its existence it is surrounded by a ring, a pulsating mesonic cloud which appears and disappears.

THE ELECTRONS SURROUNDING THE ATOM

The electrons which rotate in fixed shells around the nucleus constitute the electron cloud of the atom. They rotate around the nucleus in elliptical orbits, while the orbits themselves are grouped in particular shells. (These orbits are similar to those of the planets around the sun.)

Between the positively charged nucleus and the negatively charged electrons there are forces of mutual attraction.

According to quantum mechanics, each state of the electron in the atom is described by four numbers, which define the energy, the mechanical orbital momentum, the magnetic moment and the spin of the electrons. In each state there is only one electron, because two electrons cannot have all their quantum numbers equal.

On the basis of the energy levels (each orbit in which the electrons rotate corresponds to a definite energy state), the electrons in the atom are divided into shells and subgroups. The electrons which belong to group K have the strongest bond with the nucleus, while in the following shells – L, M, N, O, P, Q – the binding energy of the electrons is notably less.

Each shell of electrons can have only a definite number of electrons.

The electrons of the same shell are bound in the atom in almost the same way. If the electron changes orbit, jumping from one level to another, this occurs only as a consequence of absorption or emission of energy, which means a change in the energy state of the atom.

When the electron passes from one level to another nearer the nucleus, the energy of the atom diminishes and the difference is emitted in the form of electromagnetic radiation. If the jump occurs in the outer shells, the atom emits infra-red, visible and ultra-violet light.

If the electrons undergo transitions in the inner levels, enormous energy is released, and a 'hard' electromagnetic ray is emitted: the X-ray.

Electrons rotate in their orbits at enormous speed (about 1,000 km/sec.).

The atomic number in the periodic table of elements also indicates how many electrons rotate around the nucleus; since the atom is electrically neutral while in the normal state, the number of electrons in the atom must equal the number of protons in the nucleus; that is, the number of electrons surrounding the nucleus is determined by its electrical charge.

The chemical properties of the elements depend on the electrons surrounding the nucleus (the electron cloud), while the chemical valency of the atom is determined by the number of electrons in the outer shell.

The magnetic and optical properties of the atom depend on all its surrounding electrons.

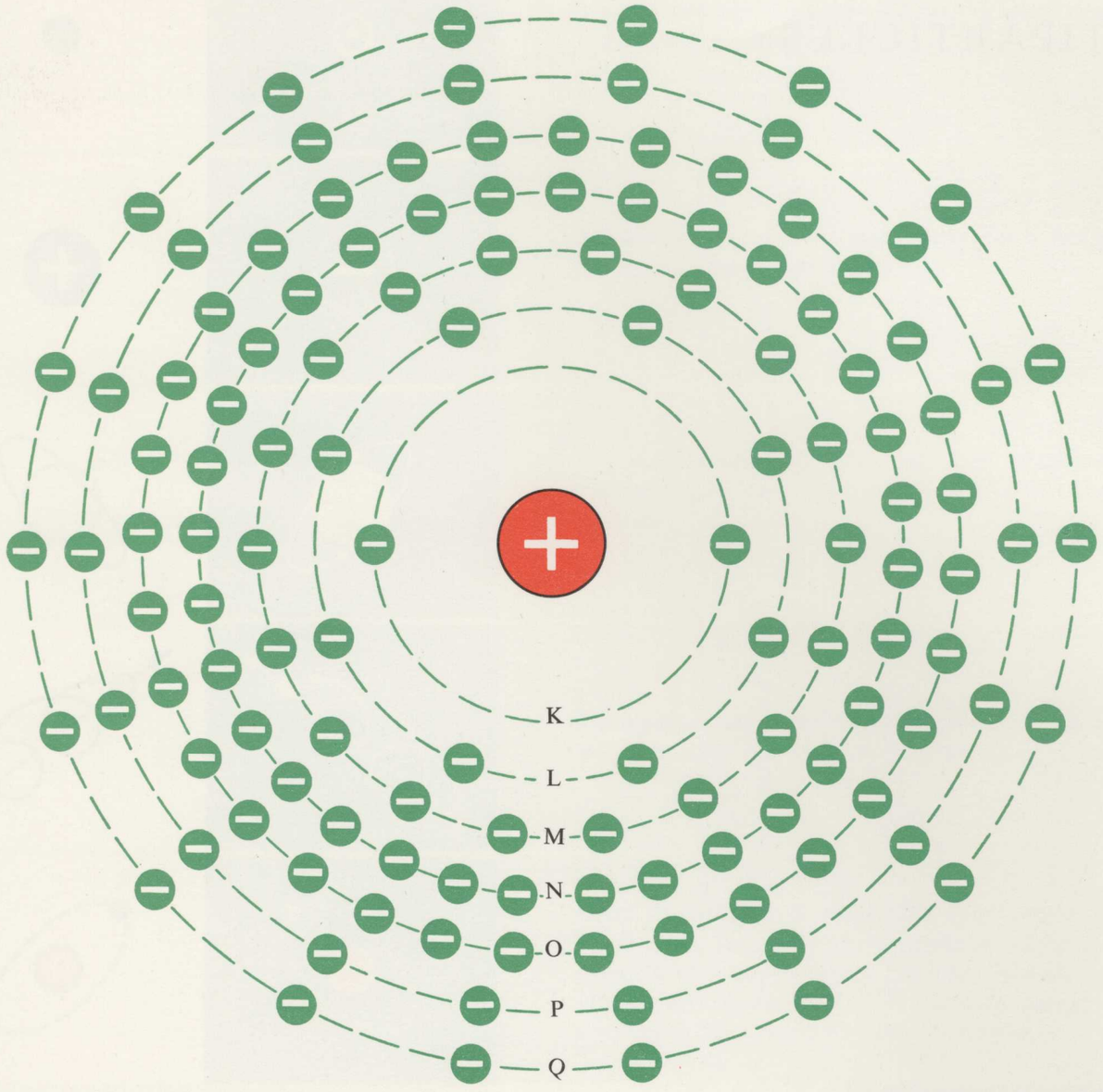


Diagram of the structure of electrons surrounding the atom

Maximum number of electrons which can be placed in the shell and subgroups

Shell	Subgroup							Number of electrons
	s	p	d	f	g	h	i	
K	2	—	—	—	—	—	—	2
L	2	6	—	—	—	—	—	8
M	2	6	10	—	—	—	—	18
N	2	6	10	14	—	—	—	32
O	2	6	10	14	18	—	—	50
P	2	6	10	14	18	22	—	72
Q	2	6	10	14	18	22	26	98

Around the positively charged atomic nucleus rotate the negatively charged electrons, which form the electron cloud (the symbols K, L, M, N, O, P and Q represent the electron shells which correspond to the values of the principle quantum number n = 1, 2, 3, 4, 5, 6, 7, while the symbols s, p, d, f, g, h, i, designate the subgroups of energy levels in the electrons, which correspond to the values of the orbital quantum number l = 0, 1, 2, 3, 4, 5, 6).

Nucleus of the atom

Electrons

ANTIPARTICLES

Research in the field of nuclear physics has shown that antiparticles exist too, that is, particles which have the same mass and spin as the elementary particles, but which have an equal but opposite charge and opposite magnetic moment. Example: electron – positron, proton – antiproton, neutron – antineutron, neutrino – antineutrino, etc.

Thus, if a particle has a charge, the antiparticle will have the opposite electrical charge, while their mass is identical.

The same thing occurs with the magnetic moment: particles exist with the same mass and opposite magnetic moment. Each electrified particle creates a magnetic field and has a definite magnetic moment: neutral particles may also have a magnetic moment.

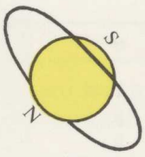
In simple terms this means that besides what we think of as normal matter, there may exist 'antimatter' in various forms. It is thought that bodies or even entire galaxies composed of 'antimatter' may exist in space and that processes of annihilation may take place between matter and antimatter.

At the level of our present knowledge, by antimatter we mean antiparticles, that is material particles with different characteristics. The expression, antimatter, is imprecise, even though it is now commonly used.

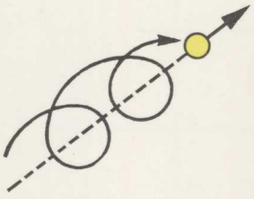
This picture is somewhat over simplified and doubtless inadequate, but the results of future research will certainly contribute to our understanding of this problem.

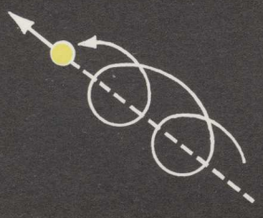
The positron has the same mass as the electron but opposite charge, that is, positive.

The antiproton is equal in mass to the proton, but has an opposite charge, that is, negative.

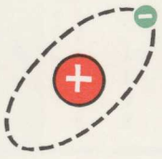


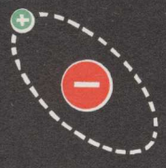
The neutron and antineutron differ only in magnetic moment; in the antineutron it is opposite to that of the neutron.





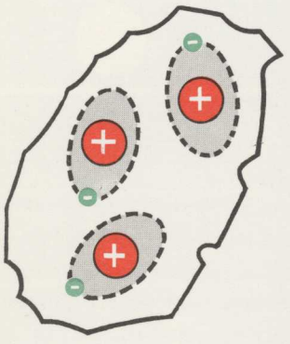
The neutrino and antineutrino differ because each has a different spin: one is left and the other right.

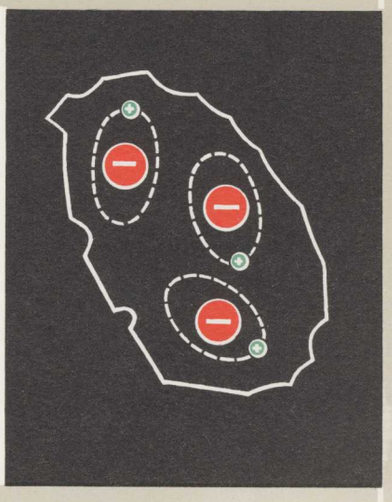




Given the existence of antiparticles, it is thought that beside atoms there may exist antiatoms as well: in their nuclei, in place of protons and neutrons, there are antiprotons and antineutrons, with positrons instead of electrons in the cloud surrounding the nucleus.

In analogy with particles and antiparticles, atoms and anti-atoms, the hypothesis has been put forward of the possibility of the existence of antimatter, that is, matter composed of anti-atoms.





Other than the elementary particles already known, of which every atom is composed, particles exist which, in their electrical and magnetic characteristics, behave in the opposite manner and thus are called antiparticles.

ELEMENTARY PARTICLES

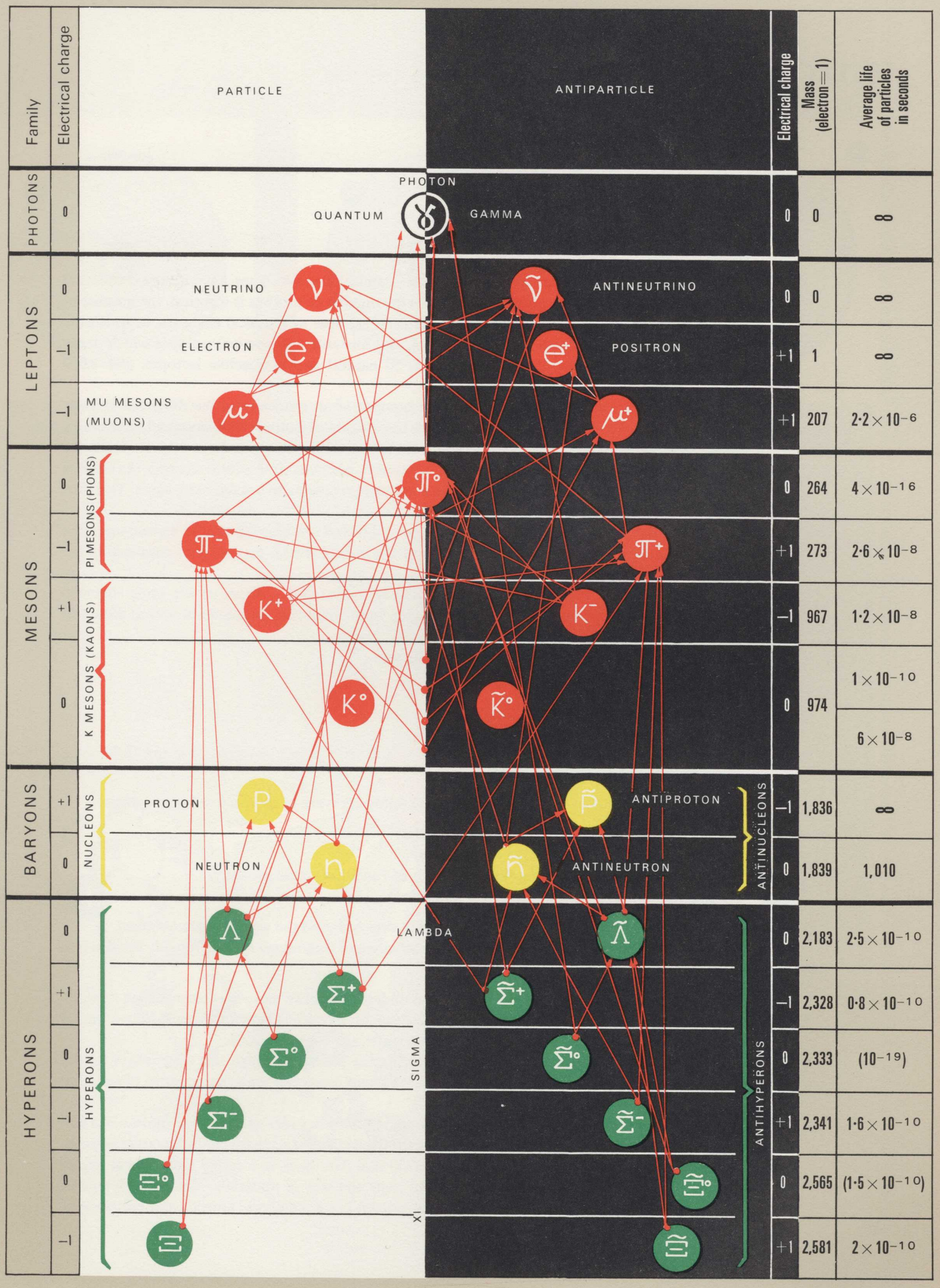
The elementary particles were named as such at a time when, on the basis of the existing knowledge of their characteristics, it was not possible to attribute a definite internal structure to them; this definition should be considered provisional because they may also be composite, physical objects. The known elementary particles, to date 32, may be classified as follows:

Type of particle	Symbol	Mass in units of electron mass	Electric charge
Photon	γ	0	0
Leptons			
Neutrino (electronic)	ν^1	0	0
Antineutrino (electronic)	ν^1	0	0
Neutrino (mesonic)	ν^2	0	0
Antineutrino (mesonic)	ν^2	0	0
Electron	e^-	1	−1
Positron	e^+	1	1
Mu (muon) plus	μ^+	207	+1
Mu (muon) minus	μ^-	207	−1
Mesons			
Pi plus	Π^+	273	+1
Pi minus	Π^-	273	−1
Pi zero	Π^0	264	0
K plus	K^+	967	+1
K minus	K^-	967	−1
K zero	K^0	974	0
Anti-K zero	K^0	974	0
Nucleons			
Proton	p	1,836	+1
Antiproton	p	1,836	−1
Neutron	n	1,839	0
Antineutron	ñ	1,839	0
Hyperons			
Lambda zero	Λ^0	2,183	0
Antilambda zero	Λ^0	2,183	0
Sigma zero	Σ^0	2,332	0
Antisigma zero	Σ^0	2,332	0
Sigma minus	Σ^-	2,341	−1
Antisigma minus	Σ^-	2,341	+1
Sigma plus	Σ^+	2,328	+1
Antisigma plus	Σ^+	2,328	−1
Xi plus	Ξ^0	2,566	0
Antixi zero	Ξ^0	2,566	0
Xi minus	Ξ^-	2,580	−1
Antixi minus	Ξ^-	2,580	+1

The coloured table represents a graphic illustration of the classification of elementary particles in five classes. To the first class belongs only one particle, the photon: quantum of electromagnetic radiation. To the second class belong the leptons: lightweight fermions. To the third the mesons: particles of mass between that of the electrons and protons inclusive, with spin 0. In the fourth class we find the baryons, comprising the nucleons, particles which form the atomic nuclei (proton and neutron) and the anti-nucleons (antiproton and antineutron). In the fifth class are the hyperons, heavy unstable particles.

Each circle in the diagram represents a point of the microcosm. Inside the circles, in Greek or Latin letters, are written the symbols chosen to designate the particles. Almost all the circles have the property of transforming themselves spontaneously into other circles, which is to say, the capacity to decay (disintegrate) as shown by the arrows. Obviously this cannot be a definitive and complete picture of the microcosm, nor would it be possible to represent it graphically. Future research should tell us more about this world.

TABLE OF THE ELEMENTARY PARTICLES AND OF THEIR PRINCIPAL CHARACTERISTICS



ISOTOPES

Isotopes are different forms of an atom of the same chemical element. They have identical chemical properties but a different relative atomic mass. While the number of protons is identical, the number of neutrons in the nucleus differs. There are stable (natural) isotopes of chemical elements, in which the nucleus may exist in a given form without decaying, and unstable (radioactive) isotopes which decay spontaneously. To date, about 250 stable isotopes, 50 natural and radioactive isotopes, and 1,000 artificial radioactive isotopes are known.

The identity of the chemical properties of the isotopes of an element and the difference in their nuclear properties, radioactivity, mass, permit a wide application of isotopes in science and technology.

The radioactive isotopes of a chemical element are the unstable ones. In order to remain stable, the nuclei of all the atoms must have a certain ratio of protons to neutrons. If this ratio changes, the nucleus becomes unstable and, transmuting, dissipates the extra energy, passing to a stable state again. This process is called radioactive decay.

The radioactivity and subdivision of isotopes into stable and unstable types both depend upon the structure of the atomic nucleus and on the energy of the bond between the particles constituting the nucleus.

Just as the radiation energy may differ enormously, radioactive isotopes of the same chemical element can have very varied periods of half-life, ranging from billionths of a second to several thousand million years.

The following types of radioactivity exist in isotopes:

alpha decay
beta decay
gamma decay
electron capture
spontaneous fission of atomic nuclei.

In relation to the character of the radiation, the following types of radioactive isotopes exist:

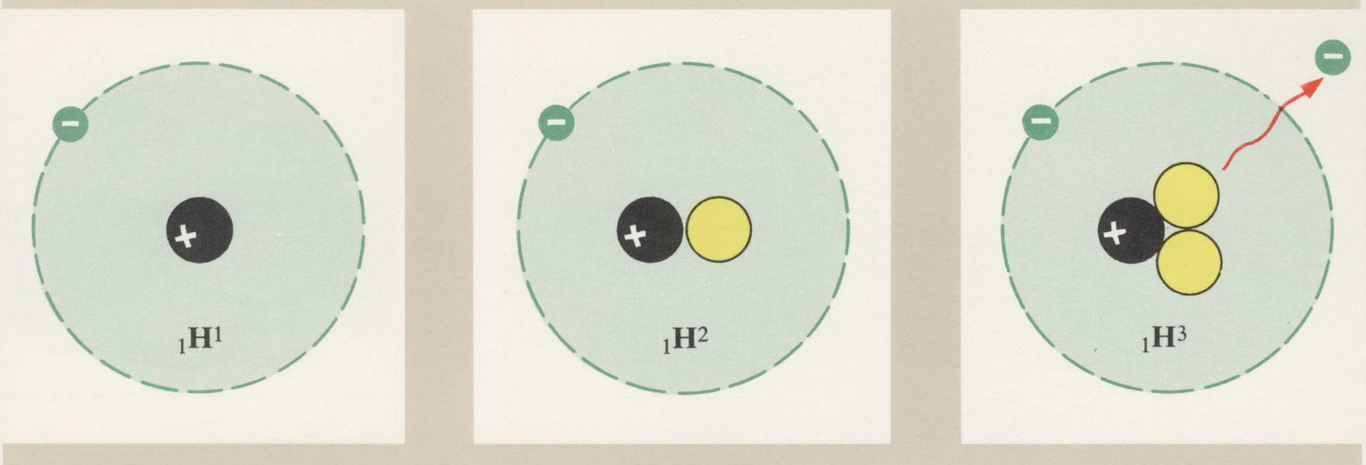
pure alpha emitters (emitting only alpha particles)
pure beta emitters (emitting only beta particles)
alpha-gamma emitters (emitting the two types; of radiation simultaneously)
beta-gamma emitters (they are the most numerous).

Radioactive isotopes may be natural or artificial, depending on the way they are obtained.

Practical application of radioactive isotopes in science and technology may be roughly divided into the following three groups:

(1) Alteration of the properties of the material under radioactive treatment (elimination of static electricity, destruction of bacteria, sterilization of foodstuffs and medicines, activation of chemical reactions, polymerization of plastic materials, therapies, etc.).
(2) Decay of energy and radiation intensity during the passage through the material (industrial and chemical radiography, measurement of bulk and density of materials, control of selection processes, packing, etc.).
(3) Marking of materials with the help of radioactive atoms in order to trace their movements and locate them. (In fluids, to mix and separate the derivatives of naphtha, to follow river courses. In solids, diffusion of metals and deposits of slime in river-beds, in locating breakages in acqueducts and canal networks, in the control of wear and tear of materials, and in every type of chemical, chemical-physical or biochemical process – e.g. catalysis, kinetics and reactions of mechanisms, etc.)

ISOTOPES OF HYDROGEN



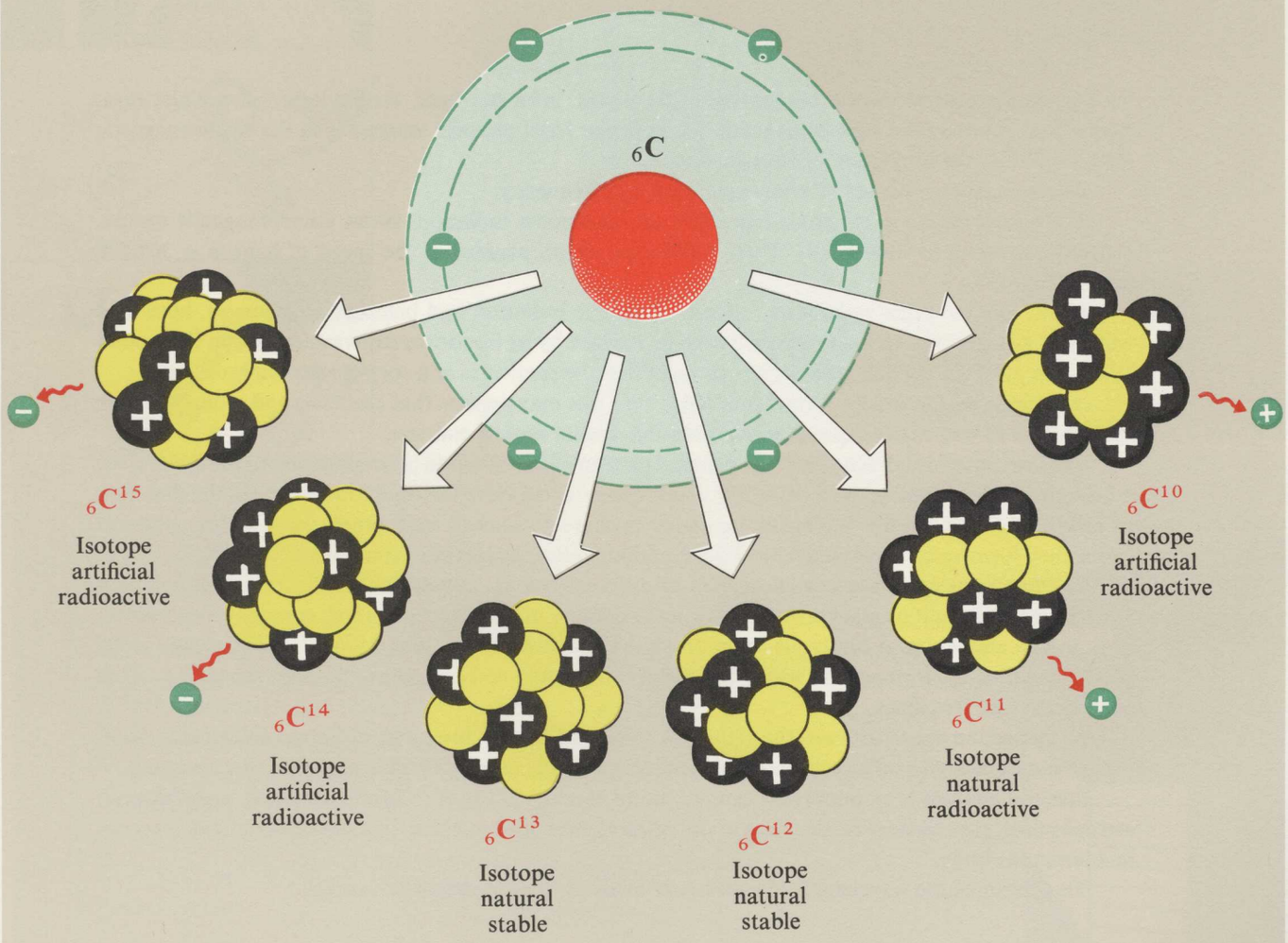
Atom of common hydrogen (light)

Atom of heavy hydrogen (deuterium) stable isotope

Atom of superheavy hydrogen (tritium) unstable isotope (radioactive)

The bottom, left-hand number indicates the atomic number Z (number of protons), while the top, right-hand number indicates the relative atomic mass. Their difference gives the number of neutrons.

ISOTOPES OF CARBON



ELECTROMAGNETIC WAVES

To the electromagnetic waves belong the radio waves, infra-red light, visible light, ultra-violet rays, X-rays and gamma rays. Electromagnetic waves derive from periodic variations in the electromagnetic field, caused by the oscillation of electrified particles.

Electromagnetic waves differ in wavelength and frequency.

The electromagnetic spectrum represents all the known radiations of an electromagnetic nature, ordered according to wavelength. These radiations are propagated at the speed of light, c = 300,000 km/sec.

Light, like the other radiations, is electromagnetic radiation and behaves in two ways, both as a wave and as a particle. In the first case it is characterized by its frequency (or wavelength), in the second by the energy of the particle; that is, it is thought that the particle is of a corpuscular-wave nature.

As electric oscillators the atoms emit light; thus one may assume that electrons and atoms oscillate in molecules at very high frequencies, representing dipolar atomic emitters.

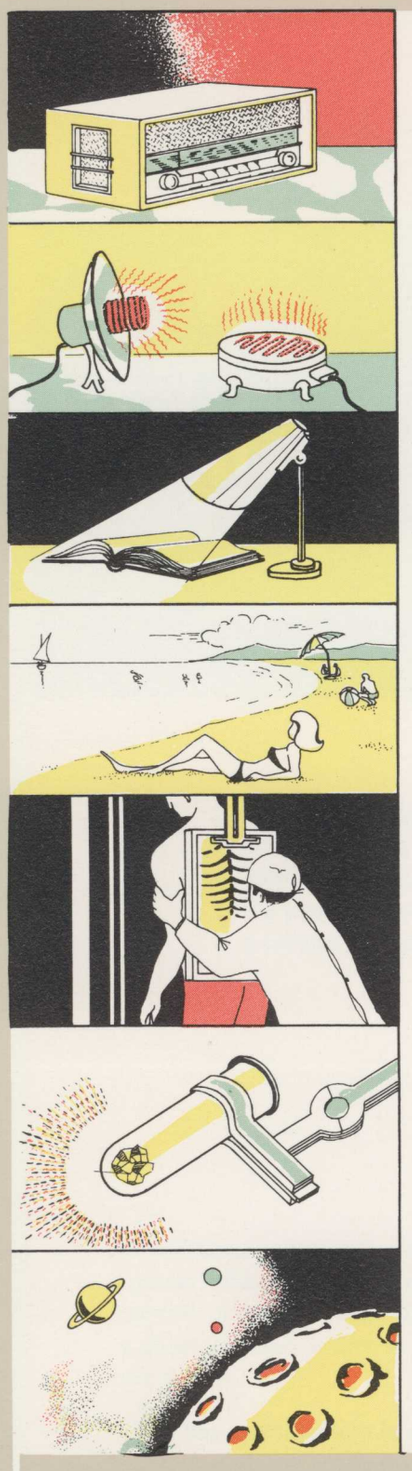
The luminous ray is a schematic geometrical pattern of the direction of propagation of the light wave; it has normal directions at the front of the wave, but oriented from the luminous source in the direction of propagation. In the flat waves the luminous rays are parallel to each other, while in the spherical waves they form vector rays which have the luminous source as centre of the sphere.

The luminous spectrum is a succession of different colours caused by the dispersion of common sunlight through a slit or glass prism. The order of colours in the spectrum is red, orange, yellow, green, blue, indigo and violet. A luminous beam of white light contains all these colours. The spectrum is the whole group of electromagnetic waves emitted by the atoms and molecules, ordered according to the wavelength and frequency.

A connection exists between the state of a substance and its luminous radiation (spectrum). Solid bodies and liquids give off a continuous or banded spectrum, gases give off a striped or line spectrum.

Spectral analysis is an important method useful in many kinds of research, chemical, metallurgical, astrophysical, etc., because on the basis of the spectral lines of an element, one may ascertain its presence in a luminous body.

To determine the wavelength of light under analysis, the spectrometer is used.



THE SOURCE AND LENGTH OF NATURAL ELECTROMAGNETIC WAVES

Radiowaves from 30,000 to 0·1 mm
($3 \times 10^{14} - 10^{7}$ Å)

Infra-red rays from 0·1 mm to 0·8 micron
($10^{7} - 7{\cdot}6 \times 10^{3}$ Å)

Visible light from 0·8 to 0·4 micron
($7{\cdot}6 \times 10^{3} - 4{\cdot}0 \times 10^{3}$ Å)

Ultra-violet rays from 0·4 to 0·01 micron
($4{\cdot}0 \times 10^{3} - 10^{2}$ Å)

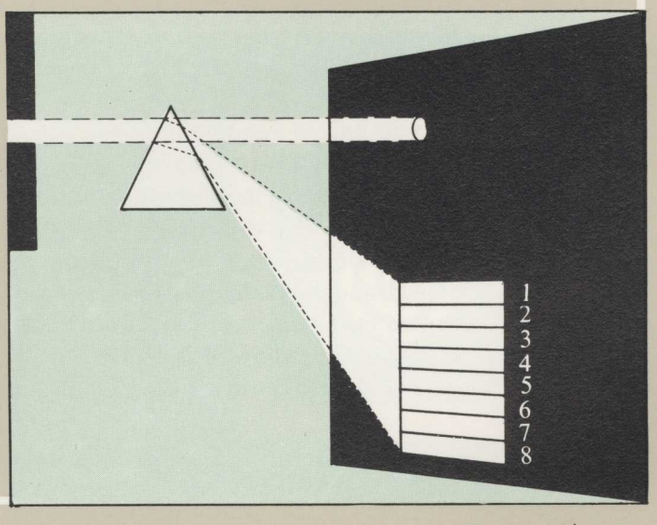
X-rays from 0·01 micron to 0·1 Å
($10^{2} - 10^{-1}$ Å)

Gamma rays from 1 Å to 0·001 Å
($1 - 10^{-3}$ Å)

Cosmic rays up to 0·001 Å

SPECTRUM OF SUNLIGHT

Infra-red rays		>7,600 Å
Visible part of the spectrum	1 red rays	7,600–6,200 Å
	2 orange rays	6,200–5,850 Å
	3 yellow rays	5,850–5,750 Å
	4 yellow–green rays	5,750–5,500 Å
	5 green rays	5,500–5,100 Å
	6 blue rays	5,100–4,800 Å
	7 indigo-blue rays	4,800–4,500 Å
	8 violet rays	4,500–4,000 Å
Ultra-violet rays		<4,000 Å



Electromagnetic waves

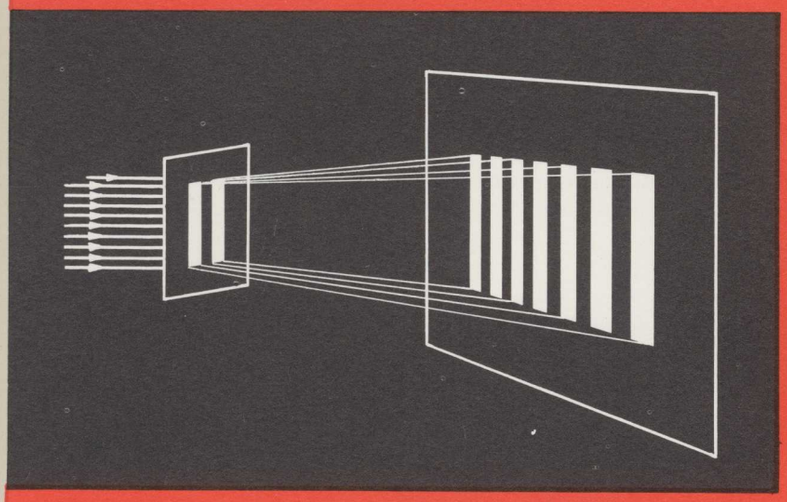
CORPUSCULAR AND WAVE PROPERTIES OF PARTICLES

In 1925–7 the phenomenon of diffraction was discovered; that is, it was proved that electrons and other particles have, till then unknown, wave characteristics.

Before this discovery, this property was attributed only to light, sound and other waves. According to traditional physics, the phenomenon of diffraction did not exist in the movement of discrete particles (electron, proton, neutron and others). Instead, it was shown that not only electron groups, but also those of neutrons and molecules of hydrogen, diffract when they come up against glass; thus the diffraction of particles is governed by the same laws that govern the phenomena of diffraction, until then thought to apply only to waves.

Diffraction is a wave phenomenon. This is shown by the spreading of a ray made to pass through a slit. When it meets the edge of an opaque body or passes through a very narrow hole, the light is scattered and deviates from its normal trajectory.

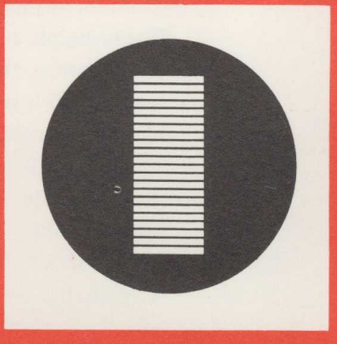
The diffraction of electrons, atoms, molecules and other particles is analogous to the diffraction of light, and shows that groups of these particles possess wave properties. From research and experiments carried out to date, one may deduce the wave-corpuscular duality of matter, as well as the properties of particles and waves in radiation. Thus it can be said that the nature of radiation and matter is twofold – corpuscular and wave-like.



When a beam of monochromatic light passes through a certain number of narrow slits close together and the rays are then gathered on a screen, diffraction will cause a series of light and dark fringes to appear on the screen.

Schematic demonstration of a device for obtaining an interference pattern from two consistent light sources, represented by two slits on the screen illuminated by monochromatic light. By using the two slits as coherent light sources, one can easily explain the phenomenon of the light and dark fringes produced on the second screen placed at a certain distance.

A diffraction grating is a device for obtaining diffraction patterns. An optical diffraction grating consists of a large number of parallel fissures, narrow and equidistant (narrow and close parallel lines engraved on a sheet of glass), drawn in such a way that the spaces between the lines act as slits.



In electrons, atoms and molecules, the diffraction phenomenon occurs when a cluster or beam of electrons, for example, comes up against a thin sheet of metallic foil. On the photographic plate placed behind the foil, light and dark concentric rings are formed. This confirms the wave nature of the electrons, that is, of particles.

QUANTUM GENERATORS AND AMPLIFIERS (LASERS)

The most recent results of quantum and electronic physics (referred to by the single name of quantum electronics) have made possible the building of the lasers.

The laser is a device for directing common light in completely parallel lines or beams, that is, without diffusion or dispersion.

The apparatus is basically composed of a spiral flash lamp and a resonance system – a ruby rod (synthetic glass ruby, of aluminium oxide, in which a certain number of aluminium atoms is replaced by chromium atoms).

The principle of the apparatus is based on the fact that atoms irradiate, emitting absolutely equal packets of energy, the quanta. Each atom behaves like a transmitting station in miniature and gives one quantum only if it is in the excited state, that is, if it has extra energy.

The crystal ruby rod is several centimetres long with a diameter of a few millimetres. The ends are smoothed and silvered like a mirror, one of them being covered by an impermeable layer of silver, while the other, the outgoing, can lose about 8 per cent of light.

The chromium atoms serve as the source of luminous atoms, excited by a strong flash from the spiral gas-neon lamp which is coiled around the cylinder with the ruby rod.

A recurring vertiginous process of multiplication of the light quanta is created in the generator. Immediately a quantum begins its journey along the glass axis it encounters the silvered mirror surface or the ruby and multiple reflection stimulates the continued generation of new quanta, thus creating an avalanche and forcing the other atoms to emit quanta of luminous energy all along the crystal axis.

To date, various types of this apparatus have been built but all are based on the same principle.

The potential applications of the lasers are almost unlimited because the direction and concentration of common light on a fixed point opens up new possibilities in the transmission of accoustic signals, television, cutting of metals, generation of energy, etc.

The fundamental limiting of existing apparatus lies in its low utilization coefficient: in fact only a small part of the energy developed can be taken advantage of.

This apparatus also has other names:

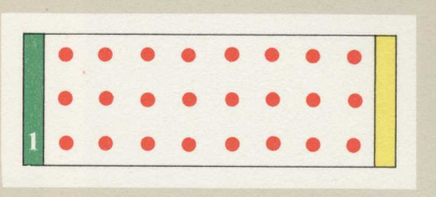
Maser, abbreviation for 'microwave amplification by stimulated emission of radiation' (apparatus for the amplification of the ultra-shortwaves of the order of millimetres and centimetres).

Laser, abbreviation for 'light amplification by stimulated emission of radiation'.

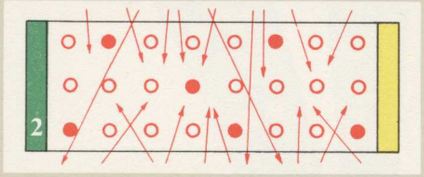
OKG = optical quantum generator (like the laser).

Iraser = apparatus for infra-red ray amplification.

Process of coherent light development with the laser

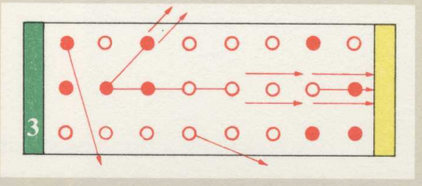


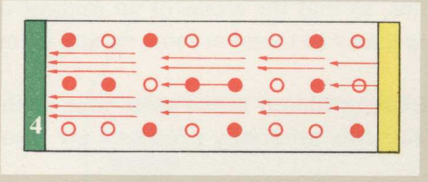
1 At the start the atoms in the laser crystal are in the unexcited state, that is, at the lowest energy level (full dots).



2 The spiral flash lamp stimulates them to an unstable, excited level, creating an avalanche of photons which amplify the light wave, while the major part of the atoms are excited (empty dots).

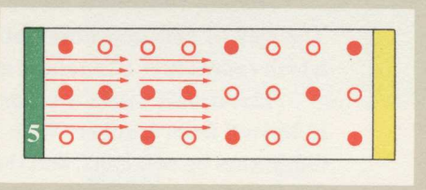
3 The atoms pass spontaneously to the excited level, that is, the avalanche begins when one of the excited atoms spontaneously emits a photon along the axis of the crystal rod. This photon stimulates another atom to emit another photon (a type of chain reaction). Photons emitted in other directions exit through the glass.

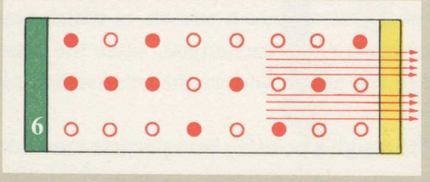




4, 5 When the excited atoms reach a certain number, the passage of one of them to the level of departure will stimulate the avalanche of transition in the others.

The process continues until the photons are reflected backwards and forwards between the mirror ends of the glass.

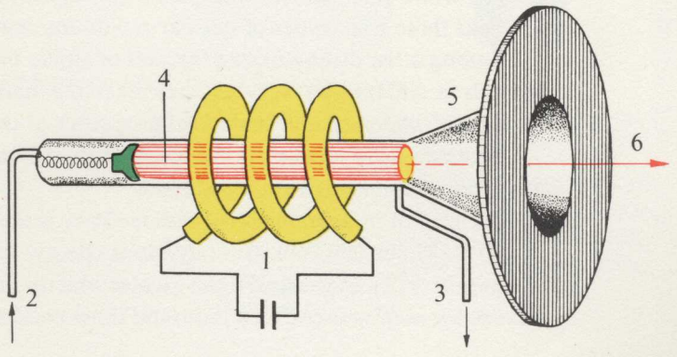




6 When amplification reaches a high enough value, part of the radiation exits through the glass and creates an intense flash of coherent light.

Diagram of the structure of a quantum generator and amplifier

1 Spiral flash lamp
2 Cooling tube (entry)
3 Cooling tube (exit)
4 Ruby crystal
5 Glass ball
6 Amplified light ray



NUCLEAR RADIATIONS

Radioactivity is the capacity of some atomic nuclei to decay spontaneously; that is, the process in which the nuclei of an element are transmuted emitting alpha, beta and gamma rays.

This property of emitting rays without an external stimulus, so that the atoms of an element or isotope are transformed into atoms of another element or isotope, may be found in some natural atoms or in artificially created atoms.

The natural radioactive elements are the radioactive isotopes produced at the same time as the formation of the other elements in nature. The radioactive elements artificially produced are those radioactive isotopes which are formed in nuclear reactions.

Nuclear radiations derive from the nuclei of radioactive atoms: the nuclei emit them during decay. The rate of emission does not depend on macrophysical changes, such as temperature or pressure, to which radioactive substances can be submitted.

The atomic nuclei are transformed with the emission of alpha and beta particles; one type of atom is derived from another. With the emission of the alpha particles, the atomic number Z of the element diminishes by two units, and the number of mass A by four. With the emission of a negative beta particle, the atomic number of the element increases by one unit; in fact it is thought that the emission of the negative beta particle is the consequence of the transformation of a neutron into a proton, in which case the nucleus finds itself with an extra proton. The mass remains practically unchanged, since the mass of the beta particle is negligible compared with the total mass of the atom, and so the relative atomic mass remains the same.

We have seen that radioactive transmutation can also occur through a positive beta particle emission or through electron capture. In this case the final atom has the same relative atomic mass as the initial one, but its atomic number diminishes by one unit.

Alpha and beta rays are, in the majority of cases, accompanied by gamma rays.

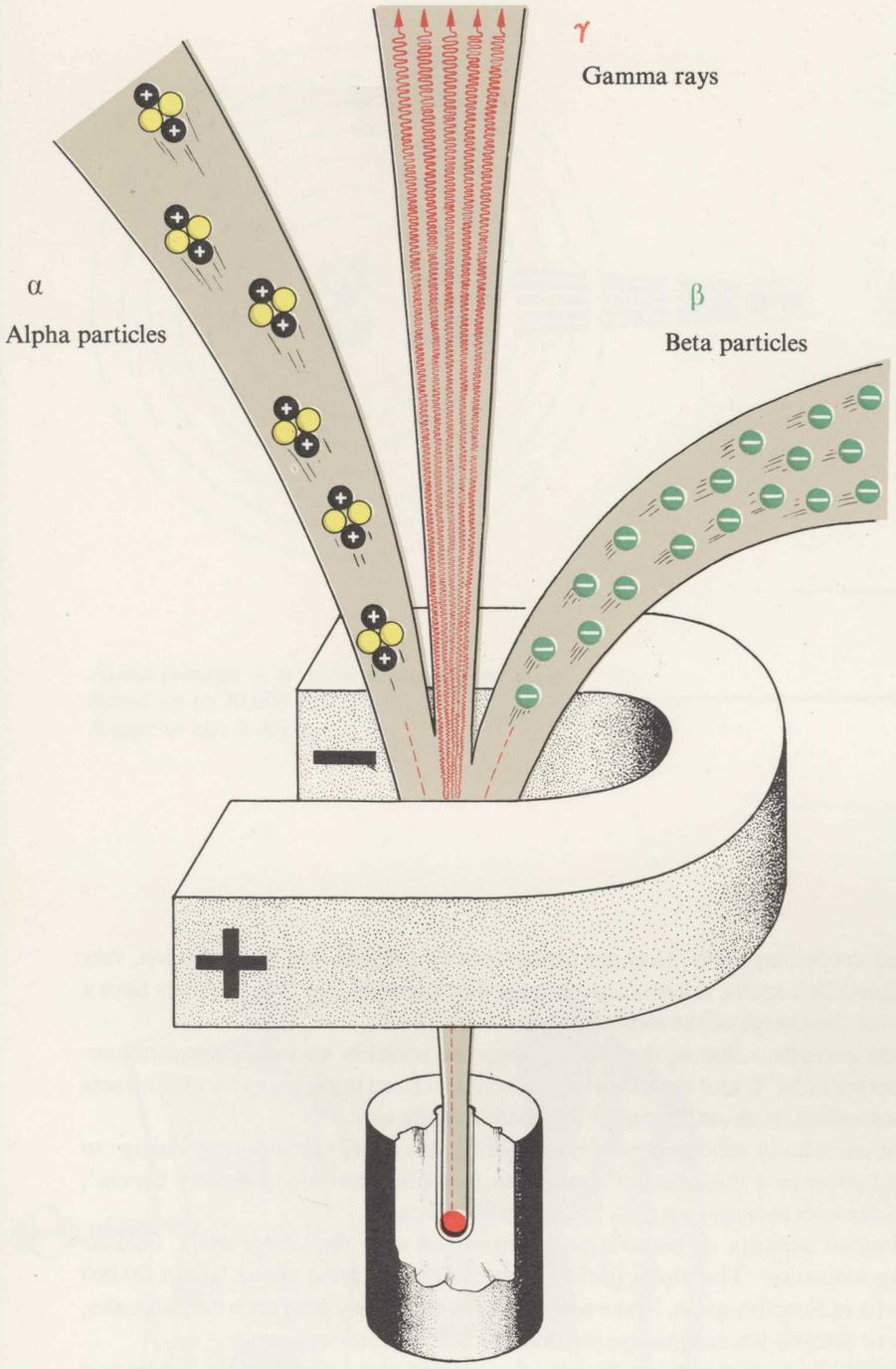
The energy spectra of emission in alpha particles and gamma rays are discontinuous (that is, line spectra), while beta particles produce a continuous spectrum.

Thus three basic types of nuclear radiations exist: *alpha*, *beta* and *gamma*.

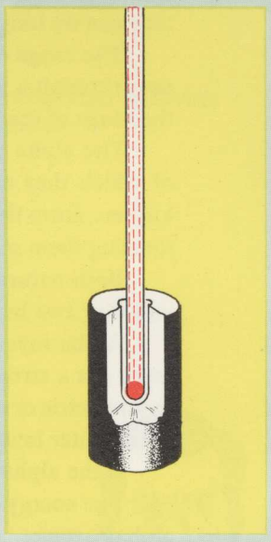
Among other distinguishing features of alpha, beta and gamma is the fact that they can pass through materials in different ways. When they reach the material, they lose a part of their energy; this may alter the physical, chemical and biological properties of the material object or living material encountered.

Neutrons have no electric charge, thus they do not react on the atom through the electric field, but only in direct collisions with the nucleus.

The unit of measurement for radioactivity is the *curie* (Ci), which is defined as the activity in which $3{\cdot}7 \times 10^{10}$ (37,000,000,000) disintegrations (decay) take place per second (dis./sec.). Multiple units are the *kilocurie* (kCi), a thousand times greater, and the *megacurie* (MCi), a million times greater; submultiple units are the *millicurie* (mCi), a thousand times smaller, and the *microcurie* (μCi), a million times smaller.



Under the action of a magnetic (or electric) field, the nuclear radiations are separated into three components:
Left side – positively charged alpha particles
Right side – negatively charged beta particles
Centre – gamma rays on which the magnetic field does not act



When they are not in an electric or magnetic field, nuclear radiations form a compact beam.

ALPHA RAYS

Alpha particles are nuclei of the helium atom. They are formed of two protons and two neutrons, very strongly linked (energy of bond 28·2 MeV), relative atomic mass 4·003 symbol α or $^{4}_{2}He^{++}$. They have a positive charge which is twice the charge of the electrons.

The 'range' of the alpha particles – that is, the distance they can travel in air under standard conditions (usually at a temperature of 15° C and atmospheric pressure 1) – from the source to a point where they can no longer create ionization, is about 10 cm for the natural alpha emitters.

The range of the alpha particles in solid materials is extraordinarily small: they do not manage to pass through a few sheets of paper or a thin sheet of aluminium, while in materials of density 1 g/cm^3, the range of the alpha particles with average energy is 50 micron (0·005 cm).

The alpha particles' limited capacity of penetration is connected with their large mass, because of which they cause strong ionization. The alpha particles are emitted at great speed, about 20,000 km/sec., from the nucleus of a radioactive atom. In the passage through air they interact with molecules, ionizing them strongly: up to 300,000 ion couples are formed on their trajectories.

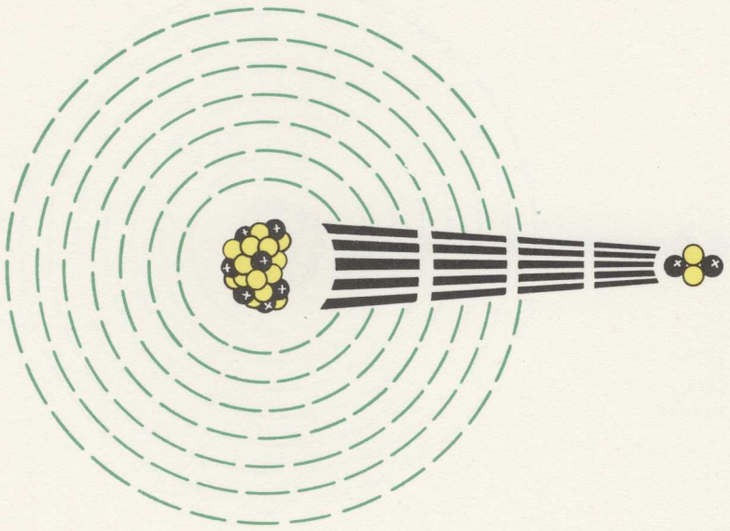
Both natural and artificial alpha-emitters exist. Twenty-five natural alpha-active nuclei are known and over two hundred artificial ones.

Alpha rays are nuclear radiations composed of alpha particles. They are not very penetrating, but carry out a strong ionizing action, cause luminescence, and react on contact with photographic plates. In an electric or magnetic field they are deflected. Given their limited penetration, they are dangerous only to the outer layers of fabrics, and thin protective materials are adequate.

If the alpha-emitter penetrates the organism, it is a dangerous source of ionizing radiation.

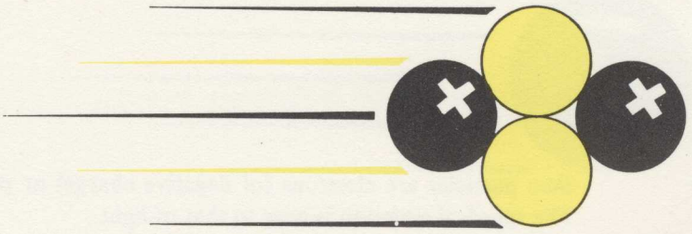
The energy of alpha rays is on average of the order of about 5 MeV. Therefore if the source of the alpha particles is outside the organism, they cannot penetrate to the basic layer of skin, and thus have no practical consequences.

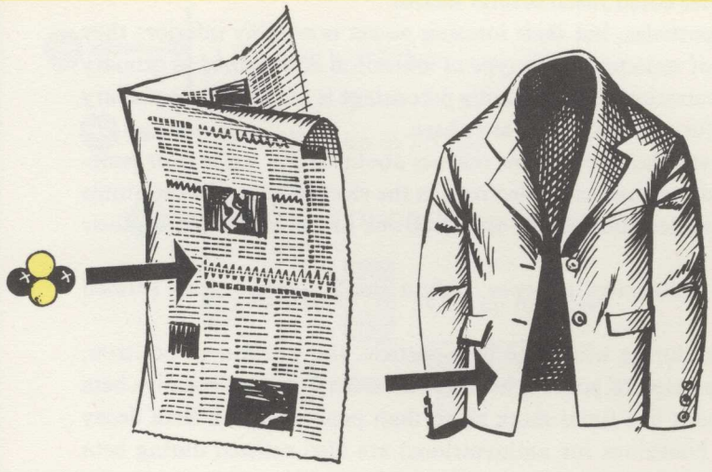
If, instead, the source of alpha particles is inside the organism (this is often the case with radioactive isotopes or materials which accumulate in the internal organs), the results are disastrous. Their properties of liberating great energy and strong, dense ionization cause in consequence the total destruction of surrounding tissue. It is thus necessary to stress the fact that a radioactive source of alpha particles constitutes one of the most dangerous forms of radiation inside the organism.



Emission of the alpha particle from the nucleus of a radioactive atom

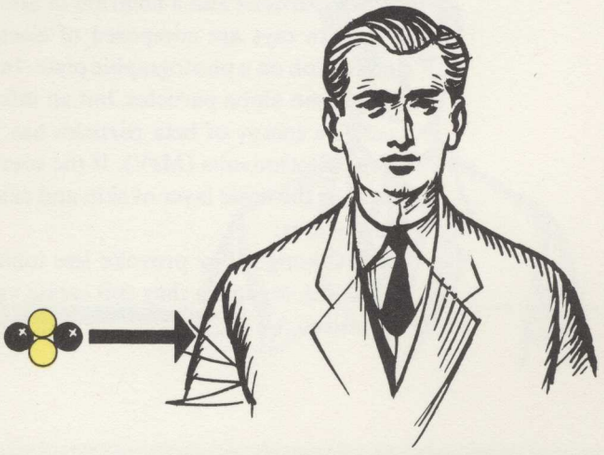
Alpha particle = nucleus of the helium atom
Speed up to 20,000 km/sec.
Range in air: 2–8 cm





Paper, clothes and other materials stop alpha particles

Alpha rays (a beam of alpha particles) cannot penetrate cloth and are not dangerous as external radiation



BETA RAYS

Beta particles are electrons (of negative charge) or positrons (of positive charge). Their symbol is β. The speed of emission is near to that of light.

While all the alpha particles of a radioactive element have the same energy, the beta particles have not. Their energy ranges from zero to very high values.

The trajectories of the beta particles are not rectilinear like those of the alpha particles, but form a broken line because they are very light and often undergo deviation after collisions with the atoms of air. In a straight line the range of the beta particles could reach several metres.

Beta particles ionize the air like alpha particles, but their ionizing power is notably inferior: they form up to a hundred ions in one centimetre of trajectory. This type of ionization is described as primary and represents 20–30 per cent of the whole ionization; the remaining percentage is ascribed to secondary ionization, that which is created by the ions formed in the primary phase.

The range of beta particles in air under standard conditions reaches about 10 cm, while their penetrative power in various materials depends on the number of electrons in the electron cloud of the atoms constituting the material, since the beta particles collide with the electrons of the cloud during their passage through the material.

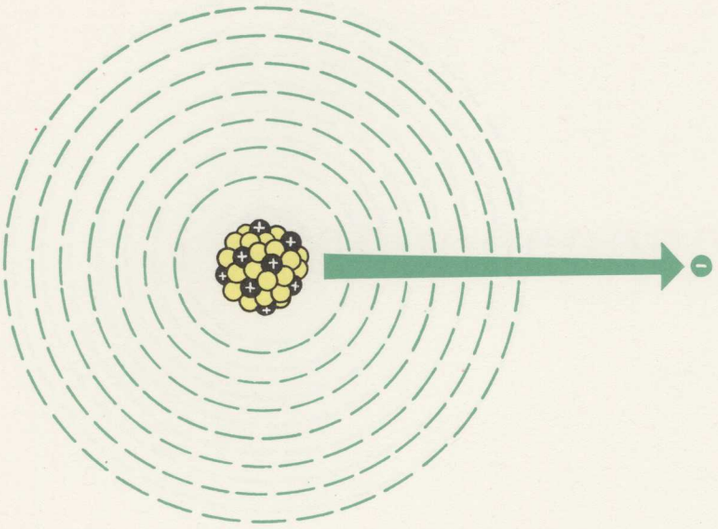
The beta-emitters are largely artificial radioactive isotopes, only a small number being formed from natural radioactive elements.

Beta emission is due to decay of atoms, during which the beta particle, the electron or positron, is emitted. Positive beta decay, that is, the emission of positive beta particles, is rarer than negative beta decay (the negative beta-emitters appear about five times more often than positive ones). Beta decay also occurs as a result of electron capture. Neutrinos (or antineutrinos) are also emitted during beta decay, and electron capture is accompanied by the emission of radiation. Beta decay is caused by the transformation, within the nucleus, of neutron to proton or vice versa, with the emission in either case of beta particles and a neutrino or antineutrino.

Beta rays are composed of electrons. They can ionize gases, cause luminescence, and make an impression on a photographic plate. In an electric or magnetic field they are deflected. They have a greater range than alpha particles, but an inferior power of ionization.

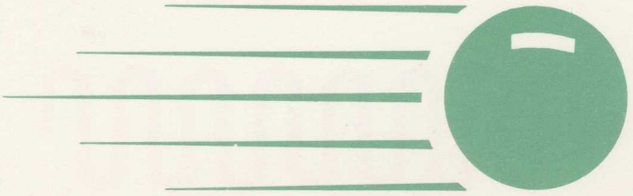
The energy of beta particles has values from a few hundred kiloelectronvolts (keV) up to several Mega-electronvolts (MeV). If the source of the beta particles is outside an organism they can penetrate as far as the basic layer of skin and cause injuries. They are harmful to the skin and especially dangerous for the eyes.

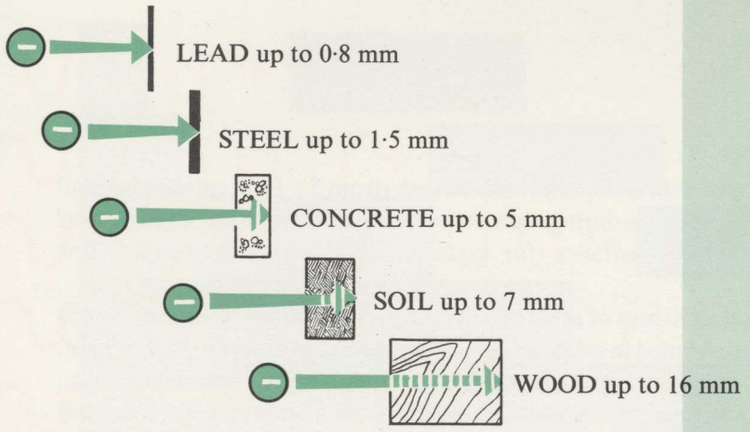
Although they provoke less ionization than alpha particles, if the source of the beta particles is inside the organism they still create very grave and complex injuries, particularly because of secondary ionization.



Emission of beta particles from the nucleus of the radioactive atom

Beta particle = electron (e−)
or positron (e+)
Speed up to 290,000 km/sec.
Range in air: several metres





Index of maximum penetration of beta rays of great energy in various materials

Beta rays (beams of beta rays) can penetrate organic tissue up to several centimetres

GAMMA RAYS

Gamma rays are electromagnetic radiations with a very short wavelength (from 3×10^{-9} cm to very small dimensions) which are formed in nuclear processes during radioactive decay of some atoms, or in nuclear reactions, or in the annihilation of pairs of particles (for example, electron-positron, etc.). Their symbol is γ.

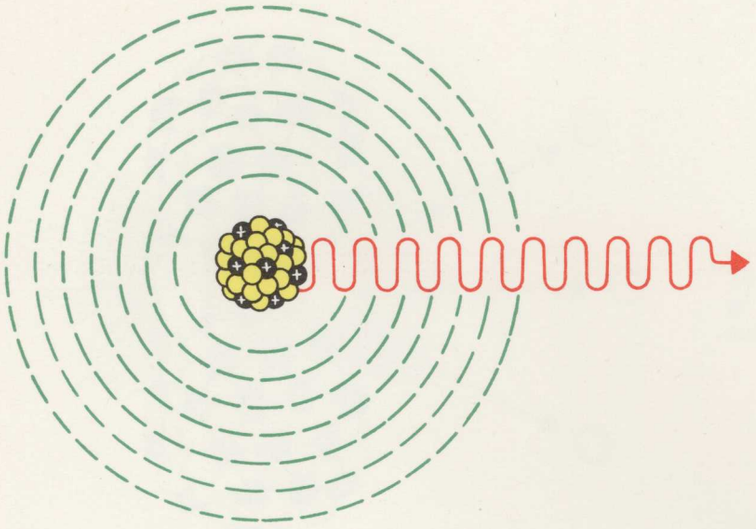
Physically, gamma rays are identical to X-rays of great energy, the only difference being that X-rays do not derive from atomic nuclei, but are formed in other ways. Their nature is identical to that of light, while the wavelength is different. The wave properties of gamma rays in diffraction, interference, etc., manifest themselves only in the longest gamma rays, while in photoeffects, in Compton scattering, they express their corpuscular properties.

Gamma rays are propagated in the form of corpuscles – photons – with an energy which starts at several keV. Their speed is equal to that of light, they have no electric charge, and compared with alpha and beta particles they have a much greater power of penetration, but a very inferior power of ionization. It is thought that the ratio of the ionization coefficient between alpha and beta particles and gamma rays is 1,000 : 100 : 1 ; that is, gamma rays form less than a couple of ions in air (at atmospheric pressure) in 1 cm of their range. This number naturally depends on the energy of radiation.

During the passage of gamma rays through material, three processes of interaction are possible (there are others but these are less important): the photoelectric effect, Compton scattering and pair formation. Gamma rays interact with the material they pass through, especially in one of the ways indicated.

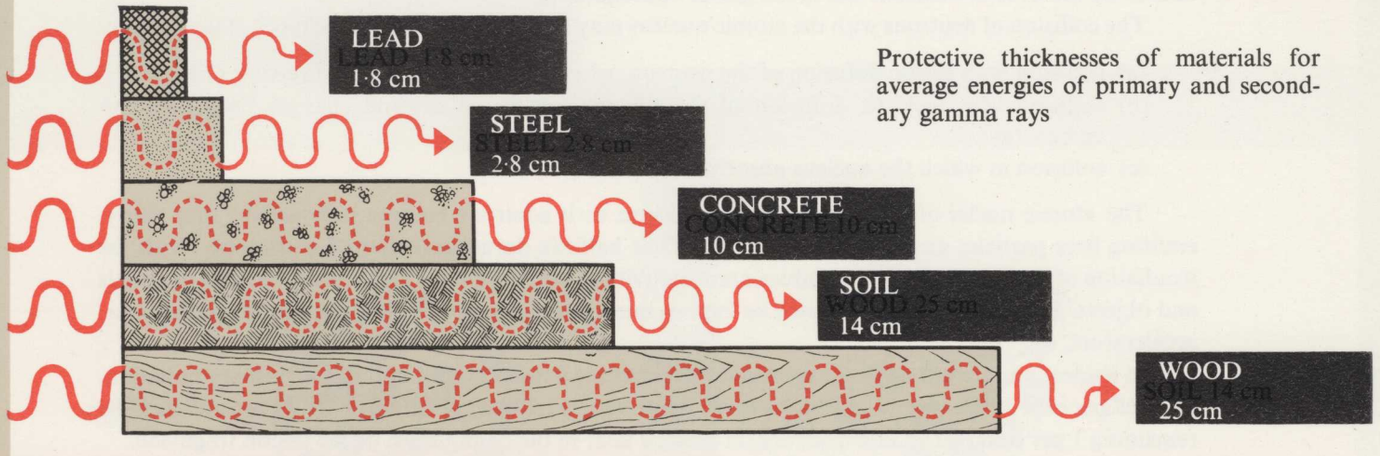
Gamma rays accompany the emission of alpha and beta particles and are emitted by nearly all the artificial radioactive isotopes and by some natural radioactive elements.

Their energy may range from a few kiloelectronvolts to over two Mega-electronvolts.



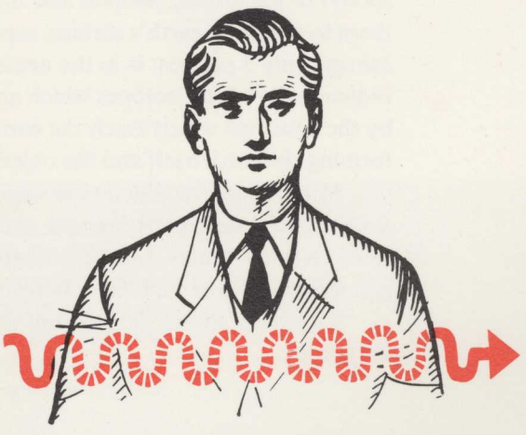
Emission of gamma rays from the nucleus of a radioactive atom

Gamma rays = electromagnetic waves
Speed = 300,000 km/sec.



Protective thicknesses of materials for average energies of primary and secondary gamma rays

Gamma rays pass through the unprotected human body



NEUTRON BEAMS

The neutron beams are corpuscular rays formed of neutrons expelled from the atomic nucleus during the process of fission. As they are without an electric charge, neutrons have strong powers of penetration and pass easily through various protective materials which stop the other rays. Thus special measures of protection are required from neutron rays. They constitute a grave danger to the organism. The extent of ionization, and hence the danger, depends on the medium penetrated; therefore the danger to individual organs is not identical, but greater in some cases and lesser in others.

If one compares a dose of neutrons with an equal dose of gamma rays or X-rays, one will find that the neutrons are from four to ten times more effective biologically. This means that the degree of damage caused by the dose of neutrons has much graver consequences.

The collision of neutrons with the atomic nucleus may occur according to three types of interaction:

(a) collision with elastic diffusion of the neutron, when the neutron changes direction only;
(b) collision with inelastic diffusion of the neutron, when the neutron changes both direction and energy;
(c) collision in which the nucleus absorbs the neutron.

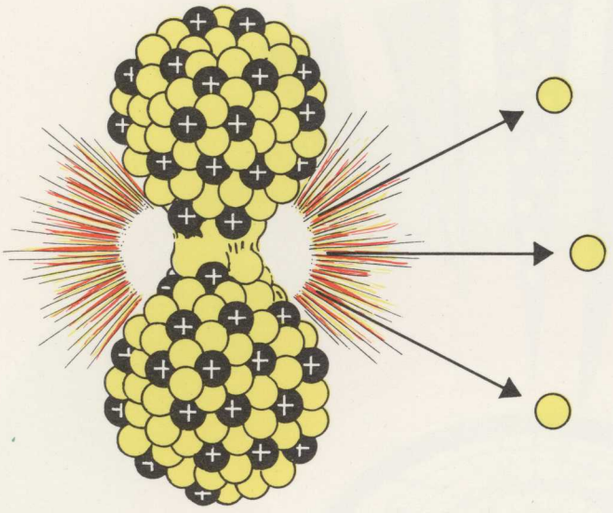
The atomic nuclei of many elements in collision with neutrons become radioactive; they decay, emitting beta particles and gamma quanta and their half-life duration is that of an isotope. With the irradiation of neutrons one obtains induced radioactivity of air, of water, of earth and of various materials and objects. Induced radioactivity must be kept in mind in the planning of nuclear reactor protections, accelerators, etc.

In nuclear and thermonuclear explosions, neutrons are a fundamental part of the primary radiation. Over 99 per cent of the energy (called the ready neutrons), is released in a time of 10^{-14} seconds and the remaining 1 per cent (called late neutrons) is emitted later in the combustion of the fission fragments.

The major part of ready neutrons is released even earlier than the decay/disintegration of the covering (body) of the atomic weapon and therefore the covering absorbs them, permitting only a small part of them to reach the earth's surface, especially if the explosion takes place in the air. Of the whole explosive energy, only 3 per cent is in the neutrons. The basic part of the secondary reaction is constituted by the radioactivity of the isotopes which are formed in an atomic explosion, following the reactions produced by the neutrons which reach the earth's surface, in combination with the atomic nuclei of the elements forming the earth itself and the objects on its surface.

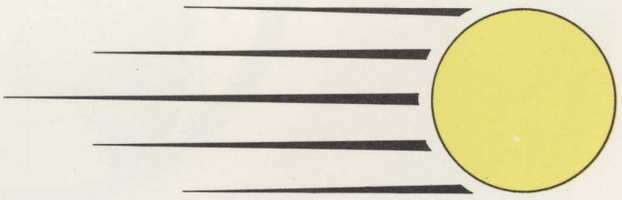
In the earth radioactive isotopes are formed of silicon, aluminium and in the main of sodium. Sodium emits beta particles with energy equal to 0·5 MeV and gamma rays with energy of 1·4 and 2·8 MeV. Neutrons may also be absorbed by the atomic nuclei of various structures and materials; the greatest induced radioactivity is reached by zinc, copper, manganese and, in a lesser measure, by iron.

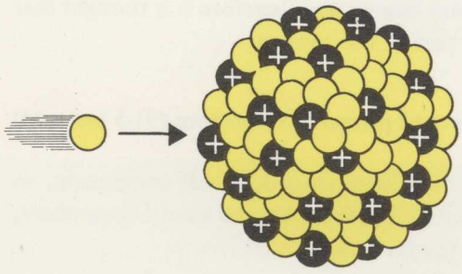
Especially strong induced radioactivity is formed in seawater after atomic explosions on or below the surface.



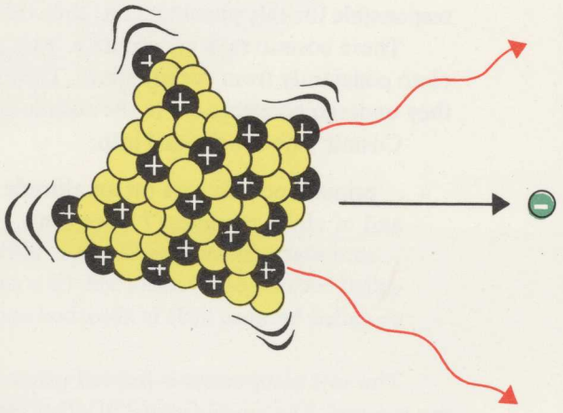
The neutrons are released in the fission of the atomic nucleus and in other nuclear reactions.

Neutron (n) = particle without electric charge





Neutrons, without electric charge, penetrate atomic nuclei easily, provoking nuclear reactions.



Neutrons produce the so-called induced radioactivity (for example, during an atomic explosion). The atomic nuclei of many elements, once penetrated by a neutron, become radioactive; they decay, emitting a beta particle and in general, gamma rays.

COSMIC RAYS

At the beginning of the twentieth century it was observed that ionization occurs in air, even air which is well isolated and dry inside a jar, it was also shown that this phenomenon takes place even if the jar is protected by a thick layer of lead, impenetrable to gamma rays.

The measurements carried out showed that ionization of air increases with altitude. On this basis the conclusion was reached that there must be a particular type of radiation coming from the cosmos, responsible for this phenomenon; thus this type of radiation was given the name of cosmic.

These cosmic rays constitute a 'rain' of elementary particles and atomic nuclei, which reach the earth constantly from cosmic space. They have an extraordinary energy and therefore it is thought that they undergo acceleration 'in the cosmic accelerator' in some part of the cosmos.

Cosmic rays are divided into:

primary cosmic rays (at an altitude of 25·30 km), composed primarily of protons (91·5 per cent) and of alpha particles (7·8 per cent).

secondary cosmic rays (at low altitudes), composed of two components: a soft component, so called because easily absorbed, (it is stopped by a lead layer 10–15 cm thick), and a hard component, so called because little is absorbed and thus it penetrates thicker absorbent layers.

The soft component is formed primarily of electrons, positrons and photons, and the hard one of mu mesons. The atomic nuclei of other elements constitute about 1 per cent.

The average energy of particles of primary cosmic radiation is in the order of 10^{10} electronvolts (eV).

As a consequence of the interaction of these radiations with atmospheric atoms, a particular component of radiation is produced, composed of neutrons and other particles. On contact with the atmosphere, the cosmic rays provoke 'cataclysms' in their collisions with atomic nuclei, creating new protons, neutrons and mesons.

As yet there is no valid theory of the origin of cosmic rays; however, there are various hypotheses on the production and nature of the various types of particles present in radiation.

The atmosphere, to which are linked electrical, thermal, light, sound and other phenomena, represents a sort of protective covering which defends living creatures from the harmful rays which reach earth constantly from the cosmos.
The atmospheric covering keeps out X-rays (1), cosmic rays (2) (primary particles), and meteors (3), while the ultra-violet rays (4) and infra-red rays (5) reach the earth in a very weakened form.

RADIOACTIVE BELTS AROUND THE EARTH

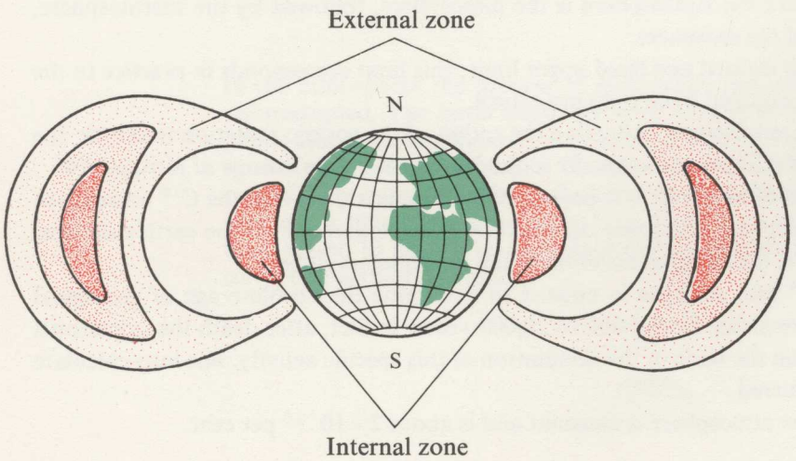
Van Allen, with the help of rockets and artificial satellites, proved the existence of two radioactive belts around our planet and its magnetic pole. They differ in length, thickness and distance from the earth's surface. They expand to north and south of the earth's magnetic equator, while in the polar zones they contract to the point of insignificance.

All the measurements made to date have shown that the space between these belts and outside them is innocuous, while it is mortally dangerous at their centre.

Radioactivity is dangerous up to 20,000 km. Space as far as the moon and beyond is innocuous, except when solar explosions occur, causing violent but brief corpuscular radiation.

Further research, with the help of rockets and artificial satellites fitted with the necessary instruments, will enable scientists to understand more about the nature of these belts, known as the 'Van Allen zones'.

Two zones of electrically charged particles surround the earth like two enormous necklaces. They were discovered with the help of artificial satellites and rockets. The existence is controlled by the earth's magnetic field. When the charged particles enter the magnetic field they may remain there 'trapped' and moving in circular orbits.



Section through the radioactive belts around the earth: the density of the dots indicates the intensity of the radiation.

Radioactive belts around the earth

NUCLEAR PROCESSES IN THE EARTH'S ATMOSPHERE

The atmosphere is a gaseous covering which envelopes the earth and to which various phenomena are bound, e.g. thermal, electric, light, sound, etc. The various physical processes which occur in the atmosphere are closely connected with others which take place on the earth's surface (soil and water) and with the influx of cosmic radiation.

The atmosphere is composed of several strata with differing physical properties. The lowest stratum is the troposphere and above it there is the stratosphere; between the two strata there is an intermediate one called the tropopause. Above the stratosphere is the mesosphere, followed by the thermosphere, while the upper stratum is called the esosphere.

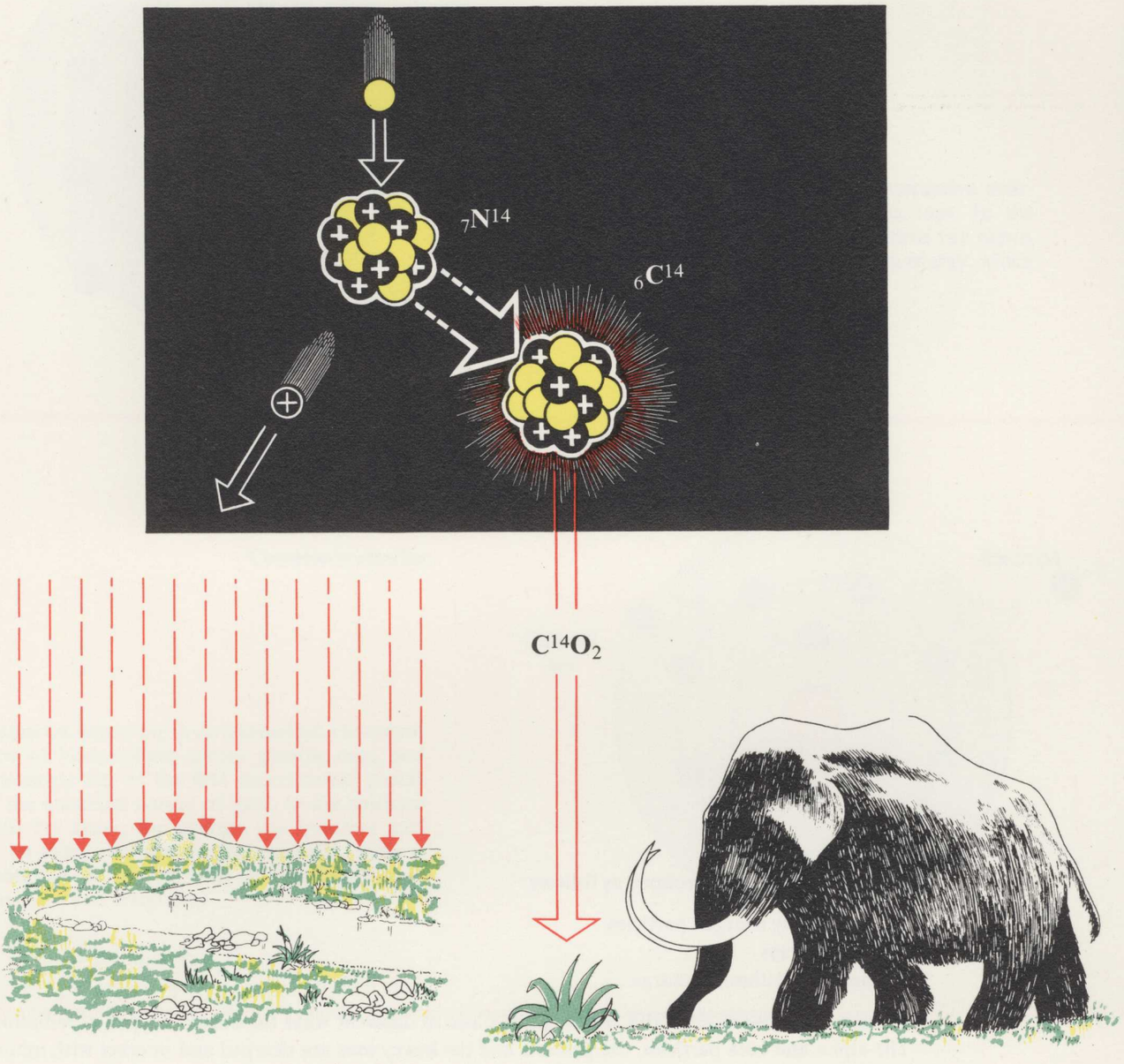
The atmosphere has no well defined and fixed upper limit; this limit corresponds in practice to the level where the molecules of air expelled from it do not return.

In the highest strata of the atmosphere, following the action of the cosmic radiation neutrons, the radioactive isotope of carbon 14 (C^{14}) is continuously formed from the stable isotope of nitrogen 14.

As a result of the movement of air (in air it is present as carbon dioxide, CO_2), the C^{14} passes continually from atmosphere to biosphere, the space occupied by living organisms on the earth's surface, air, water, and to the lithosphere, the external covering of the terraqueous globe.

The transformation of C^{14} into nitrogen is utilized to determine the absolute age of geological formations and archaeological remains, from 1,000 to 30,000 years. In fact, after death the organism's assimilation of C^{14} ceases, and on the basis of the diminution of this specific activity, one may calculate the time elapsed since death occurred.

The percentage of C^{14} in the atmosphere is constant and is about 2×10^{-10} per cent.



In the atmosphere the process of radioactive isotope formation in carbon is uninterrupted. The latter combines with oxygen to form carbon dioxide. As plants absorb carbon dioxide, the animals which feed on them store up a certain quantity of radioactive carbon 14. After the death of the plant or animal, it is possible, by measuring the radioactive decay in their remains, to determine how much time has elapsed since they died; from the moment of death they have ceased to absorb or assimilate carbon dioxide in which the radioactive isotope of carbon is found.

Nuclear processes in the earth's atmosphere

INTERACTION BETWEEN RADIATION AND MATTER

Nuclear radiations can be grouped as follows:

(a) electrically charged particles
(b) gamma rays
(c) particles without a charge.

Consequently interaction with matter takes place in different ways for different types of radiation.

The alpha and beta particles, the protons and the heavy ions are charged and interact with matter with which they come into contact, ionizing it.

Ionization occurs as a consequence of the action of the electric field around a charged particle, and not as a consequence of direct collision (understood in the classic, macroscopic sense) with the atom. The charged particles interact with the covering of the atom; only when they possess high energy can they interact with the nucleus.

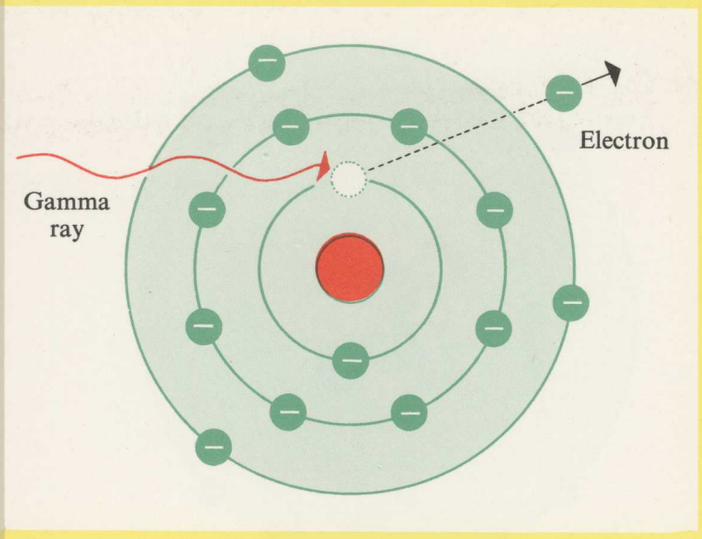
In every ionization process, alpha and beta particles, protons and heavy ions lose part of their energy and subsequently move more slowly.

The interaction between gamma rays and matter is demonstrated in the diagrams.

The interaction of neutrons which have no electric charge occurs with the atomic nucleus. There are three types of interaction:

collision with elastic diffusion of neutrons
collision with inelastic diffusion of neutrons
collision in which the atom absorbs the neutron.

The nuclear transformations which occur in collisions of neutrons and other particles with the atomic nucleus are called nuclear reactions.

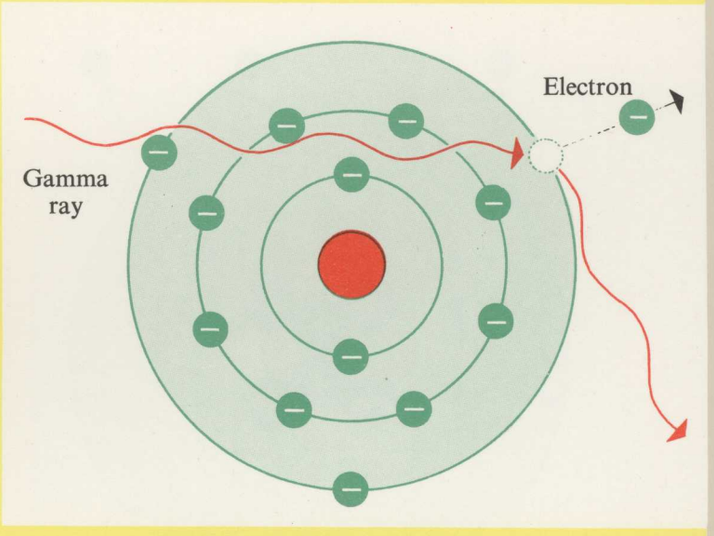


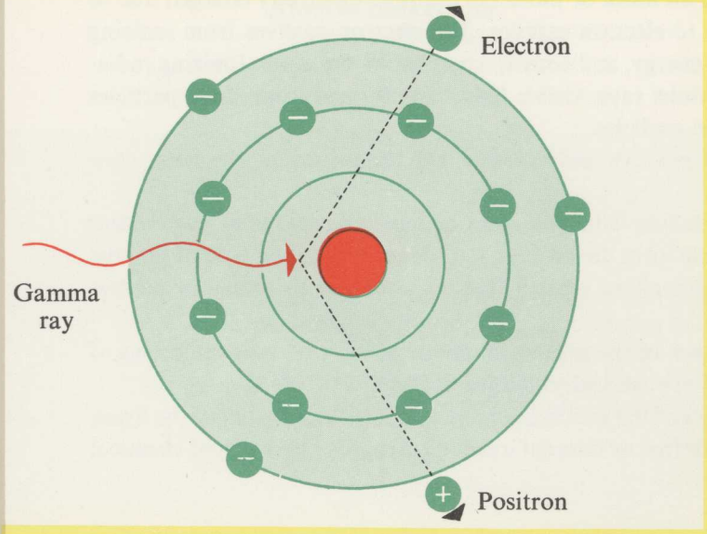
Photoelectric effect

The photoelectric effect is an interaction characteristic of low energy gamma rays. In the collision with the atom, the gamma ray expels an electron, dissipating all its own energy, which passes to the electron.

Compton scattering

Compton scattering is an interaction characteristic of intermediate energy gamma rays, and represents one of the first experimental proofs of the quantum nature of light. In the collision with the atom, the gamma ray transfers part of its energy to the electron emitted, while it continues to move with a modification of direction and frequency.





Pair formation

This process is an interaction characteristic of high energy gamma rays. In the collision with the atomic nucleus, two particles are formed: the electron and the positron.

IONIZATION

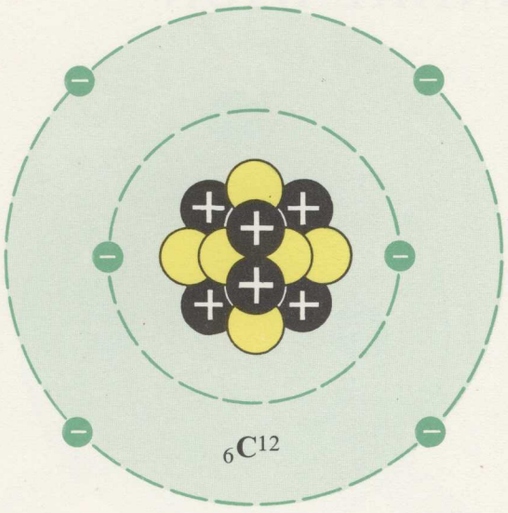
Ionization is the transformation of atoms or neutral molecules into particles of positive or negative charge called ions. This is a process in which an atom or molecule becomes positively charged due to electron emission, or negatively charged due to electron capture. The electron receives from ionizing radiations an energy greater than the binding energy, and consequently leaves the atom. Ionizing radiations include the gamma rays, X-rays, ultra-violet rays, visible light, rays formed from alpha particles and from protons, electrons and other charged particles.

As a consequence of ionization, pairs of positive and negative ions are produced, the latter constituted essentially of electrons.

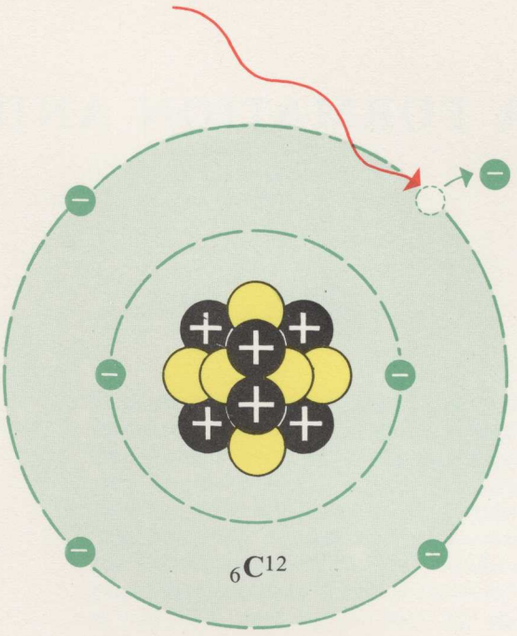
In gases, ionization occurs with the extraction from the atom or molecule of one or more outer electrons; the atom and the remaining molecule form the positive ion. According to the type of gas, the electrons separated from the atom or molecule either remain free, or couple with atoms or neutral molecules of the gas, forming negative ions.

In solutions (electrolytes), ionization occurs in the process of dissociation where the molecules of the solute split into ionized atoms and groups of electrically charged atoms.

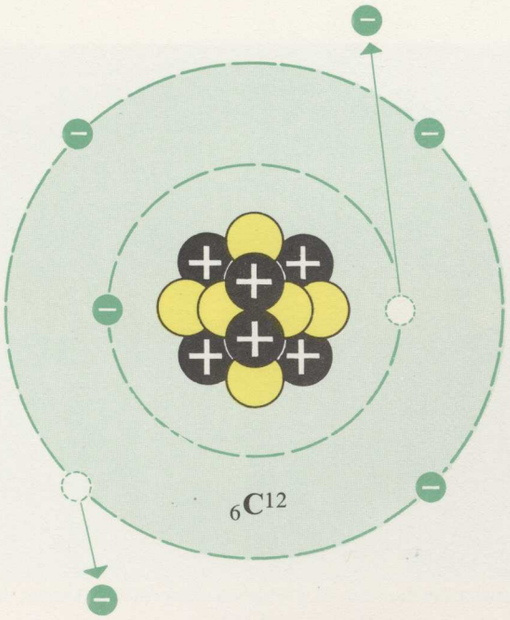
Although there is as yet no complete theory of the action of ionizing radiation in tissues of the living organism, nevertheless it is well known that external or internal irradiation causes physical and chemical alterations in it.



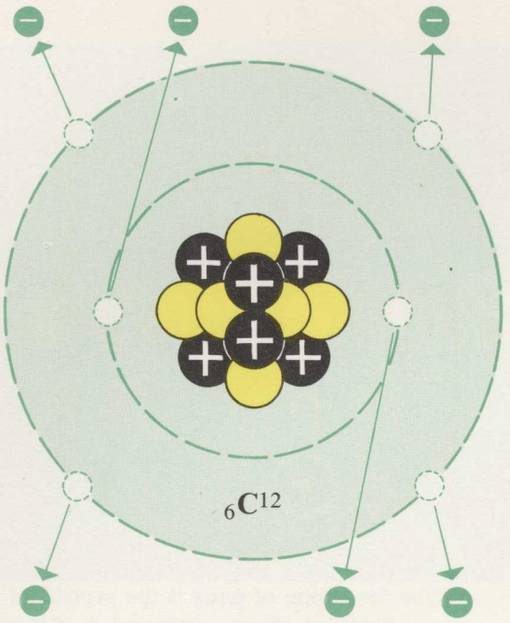
Atom of carbon in the normal state



Ionization of an atom of carbon



Atom of carbon with double ionization



Atom of carbon completely ionized

The ion is an atom or molecule which possesses a positive or negative charge. According to the increase or decrease in the number of electrons relative to the normal state, positive or negative ions are formed. The positive ion is the residue of the atom after the expulsion of an electron. The electron expelled remains free, or is captured by another atom which thus becomes a negative ion.

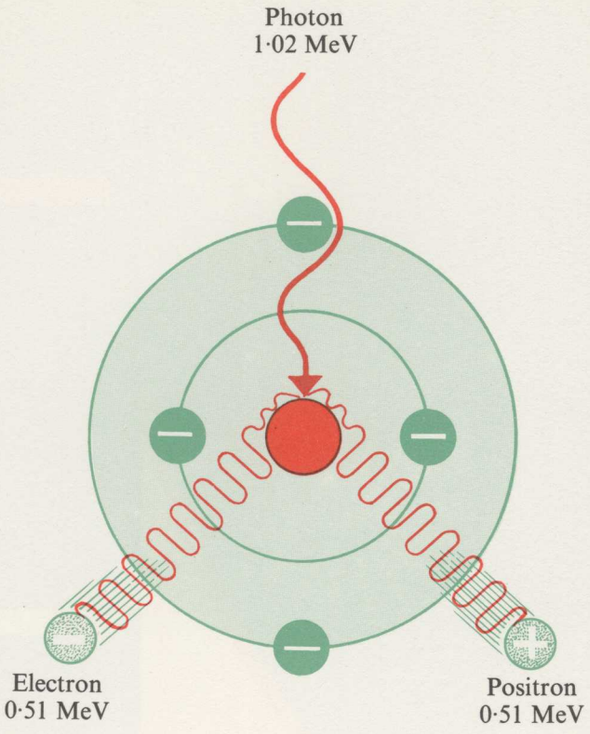
PAIR FORMATION AND ANNIHILATION

The formation of pairs is the process of simultaneous production of particles and antiparticles; more precisely, it is the transformation of high energy photons, in collision with the atomic nucleus or with another particle, into an electron-positron pair. This process may also occur in the collision of an electron with an atomic nucleus or with another particle.

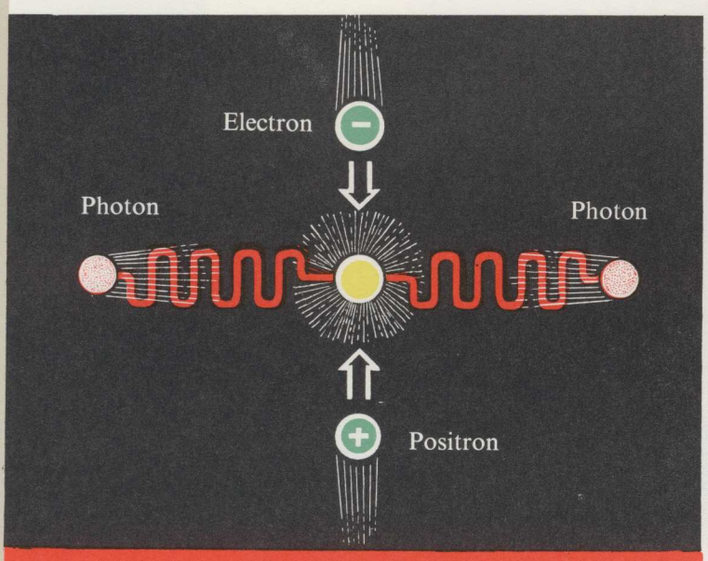
A high energy gamma ray may in certain conditions transform itself into an electron-positron pair – that is, into particles. This demonstrates once again, the duality of matter, waves and particles and the transformation of one form of matter into another.

Annihilation is the transformation of pairs of particles into photons; that is, the inverse of the pair formation process. For example, in the collision of a positron with an electron, both particles are annihilated and gamma rays produced. The energy of the electron-positron pair, both kinetic and that linked with their rest mass, is transferred to the photons. The annihilation of other particles is also known to occur, for example of protons and antiprotons, which gives place to the formation of pi-mesons and k-mesons.

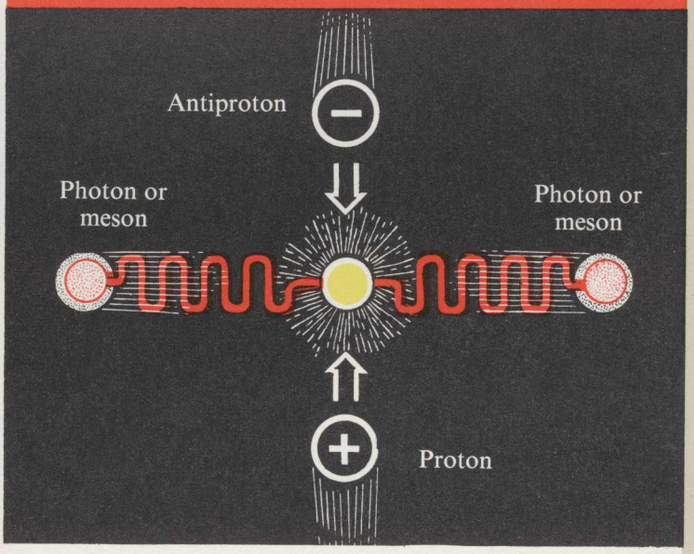
The term annihilation is not quite exact, since the Latin *annihilatio* means destruction, while in the phenomenon explained it is merely a question of the passage from one state of matter to another. In annihilation the mass and energy of the system of particles, their momentum and their charge, all remain unchanged.



High energy photons in collision with the atomic nucleus or with other particles are transformed into an electron–positron pair. In the process of pair formation, particles and antiparticles are created. The minimum photon energy necessary for the formation of the pair, electron–positron, electron (e^-) and positron (e^+), is 1·02 MeV, that is, 0·51 MeV for each particle; this corresponds to the rest mass of the electron.



When electron and positron meet they are annihilated, transforming themselves into two gamma rays with an energy of at least 0·51 MeV each.



The annihilation of other particles is also known to occur, for example, of protons and antiprotons: photons or mesons are derived.

Annihilation is the inverse process of pair formation, that is, the transformation of particles and antiparticles into photons or, in the case of protons and antiprotons, to photons and other particles.

HALF-LIFE

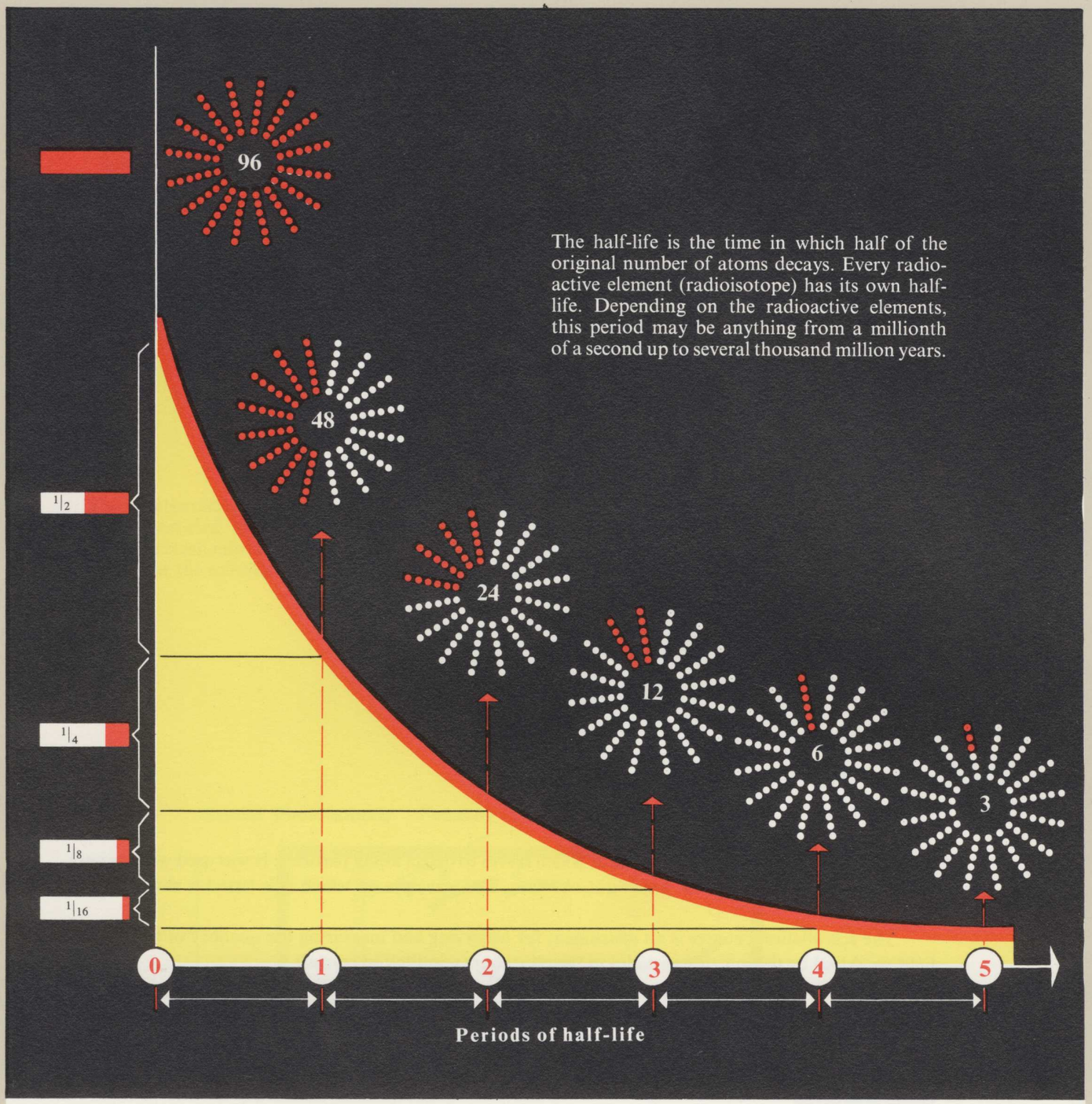
The half-life ($T_{\frac{1}{2}}$) of a radioactive isotope is the time in which half of the atoms initially present, decay or disintegrate.

Half-life is one of the basic characteristics of radioactive substances; that is, it is the constant characteristic of every particular radioisotope and may vary from one billionth of a second to several thousand million years. Different radioactive isotopes of an element can have different half-lives and present different types and energy of radiation.

The reciprocal value of the half-life is called the decay constant.

Radioactive decay is not linear (proportional) in time, because the number of nuclei which decay depends on the number of radioactive atoms present. The number of radioactive atoms still undecayed does not diminish in a linear manner, in time, but decreases in an exponential manner.

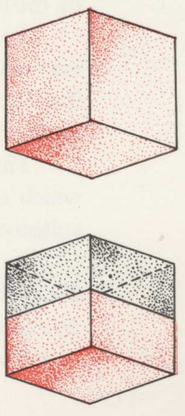
The law of radioactive decay is expressed by the ratio between the number of undecayed nuclei of a certain quantity of radioactive substance and the time, so that, after one period of half-life, half the initial number of nuclei remains, after two periods, a quarter remains, and after three, an eighth.



The half-life is the time in which half of the original number of atoms decays. Every radioactive element (radioisotope) has its own half-life. Depending on the radioactive elements, this period may be anything from a millionth of a second up to several thousand million years.

SOME RADIOACTIVE ELEMENTS AND THEIR LENGTHS OF HALF-LIFE

U URANIUM 235	$4{\cdot}5 \times 10^9$ years (4·5 thousand million years)	**Au** GOLD 98	2·7 days
Ra RADIUM 226	1,600 years	**Na** SODIUM 24	15 hours
Co COBALT 60	5·3 years	**Cu** COPPER 66	5·22 minutes
S SULPHUR 35	88 days	**Zn** ZINC 67	9×10^{-6} seconds (9 millionths of a second)



SPINTHARISCOPE AND SCINTILLATION COUNTER

The spinthariscope is a piece of apparatus which serves to detect alpha particles. It was used with success at the start of the nuclear era, but is not obsolete. The principle on which it is based is shown in the diagram.

The scintillation counter is an instrument for observing and measuring the quantity of fluorescent light produced by the ionizing particles in the phosphor (scintillation crystal).

Scintillation counters are the most common counters for nuclear radiations. Their basic characteristics are: high detection efficiency, high speed reaction to the passage of radiations, minimum dead time and response proportional to the energy of radiation.

These counters are based on the principle that certain organic and inorganic substances sparkle under the action of ionizing radiations. Sodium iodide is most commonly used for gamma rays, zinc sulphide for alpha rays, a mixture of zinc sulphide and plexiglass for fast neutrons, and a mixture of zinc sulphide and boron for slow neutrons.

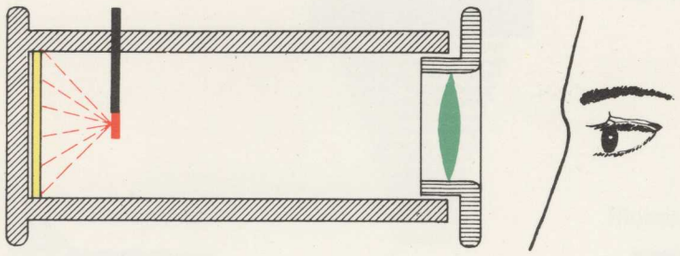
The intensity of scintillation in these substances is proportional to the dissipated energy of the radiation which causes it, but in the majority of cases the scintillation is so weak that it cannot be seen by the naked eye.

To record the radiation, devices are used which transform the luminous impulses (scintillations) into electric impulses. A photo-electric cell is the simplest device. The impulse which is obtained from it is unfortunately very small and it is thus very difficult to utilize it. Therefore special electronic tubes are used which are called electron photomultipliers.

The photomultiplier makes use of the phenomenon of secondary emission of electrons (a phenomenon which occurs when fast electrons collide with certain materials, and consists in the fact that in each collision the electron extracts two or more electrons from the material).

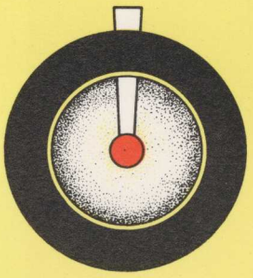
By applying suitable potentials to a special arrangement of several electrodes, known as dynodes, for each collision of electron and dynode, one can obtain the extraction of two or more electrons; and by repeating the process on every dynode, an avalanche of a million electrons for each original electron.

The diagram shows the mechanism and function of the scintillation counter.



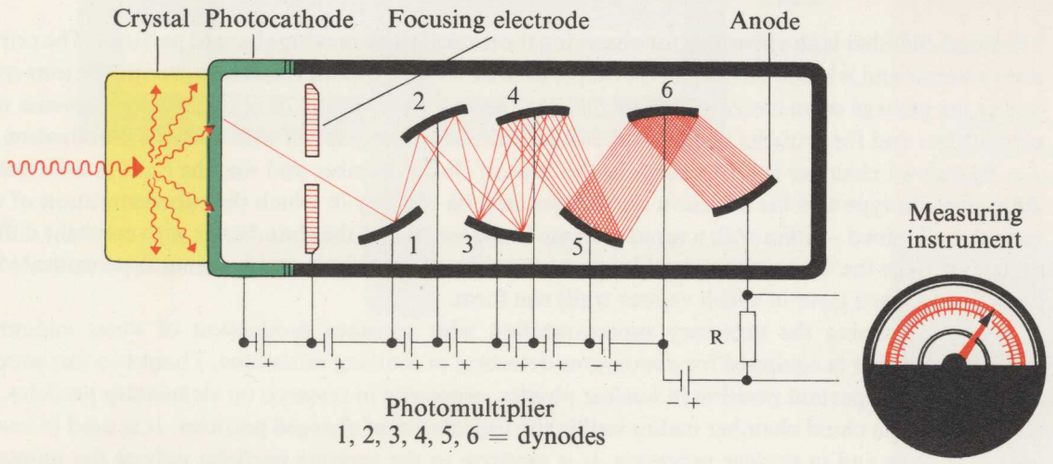
SPINTHARISCOPE

Through the lens of the spinthariscope one can observe the scintillation which occurs following the collision of alpha particles with the screen.



The spinthariscope is a piece of apparatus which serves to detect alpha particles. After leaving the radioactive substance, alpha particles crash into the screen covered by a thin layer of zinc sulphide and cause the scintillation which can be seen through the lens.

SCINTILLATION COUNTER



Photomultiplier
1, 2, 3, 4, 5, 6 = dynodes

In its passage through the crystal, the ionizing particle causes scintillation. When a quantum of this light falls on the photocathode, it releases electrons. These electrons are focused by the electrode which is set behind the photocathode, in the form of a plate with a round aperture. Further forward there is a series of emitter electrodes (dynodes 1, 2, 3, 4, 5, 6) and at the end there is the final anode. Potential is minimum on the photocathode, while on the last electrode (anode) it is maximum. The electrons expelled by the photocathode in the photomultiplier multiply in number and accelerate, because when each electron falls on the electrode, it expels 2–4 new electrons. The difference of potential between the first and last dynode may reach about 1,500 volts.

THE WILSON CLOUD CHAMBER

The cloud chamber is an apparatus for observing the tracks left by moving charged particles. The principle is very simple and is based on the fact that supersaturated water vapour condenses around the ions created during the passage of an ionizing particle through the gas. The droplets develop until they assume visible proportions and form tracks which can be observed and photographed with suitable illumination.

The cloud chamber is also known as the Wilson cloud chamber and may be built in two versions, the expansion type and the diffusion type, depending on the way in which the supersaturation of water vapour is obtained – either with a rapid increase in the volume of the chamber or with constant diffusion of vapour from the warmer to the colder part where the vapour cools and becomes supersaturated, it is possible to form a layer in which vapour trails can form.

By maintaining the necessary supersaturation with constant production of water vapour, the diffusion chamber is equipped for continuous detection of ionizing radiations. Thanks to this property, it occupies an important position in nuclear physics, especially in research on elementary particles.

The Wilson cloud chamber makes visible the trajectories of charged particles. It is used in research on cosmic rays and in nuclear processes. It is sensitive to the ionizing particles only at the moment of expansion, when, that is, the right conditions exist for obtaining a supersaturated vapour.

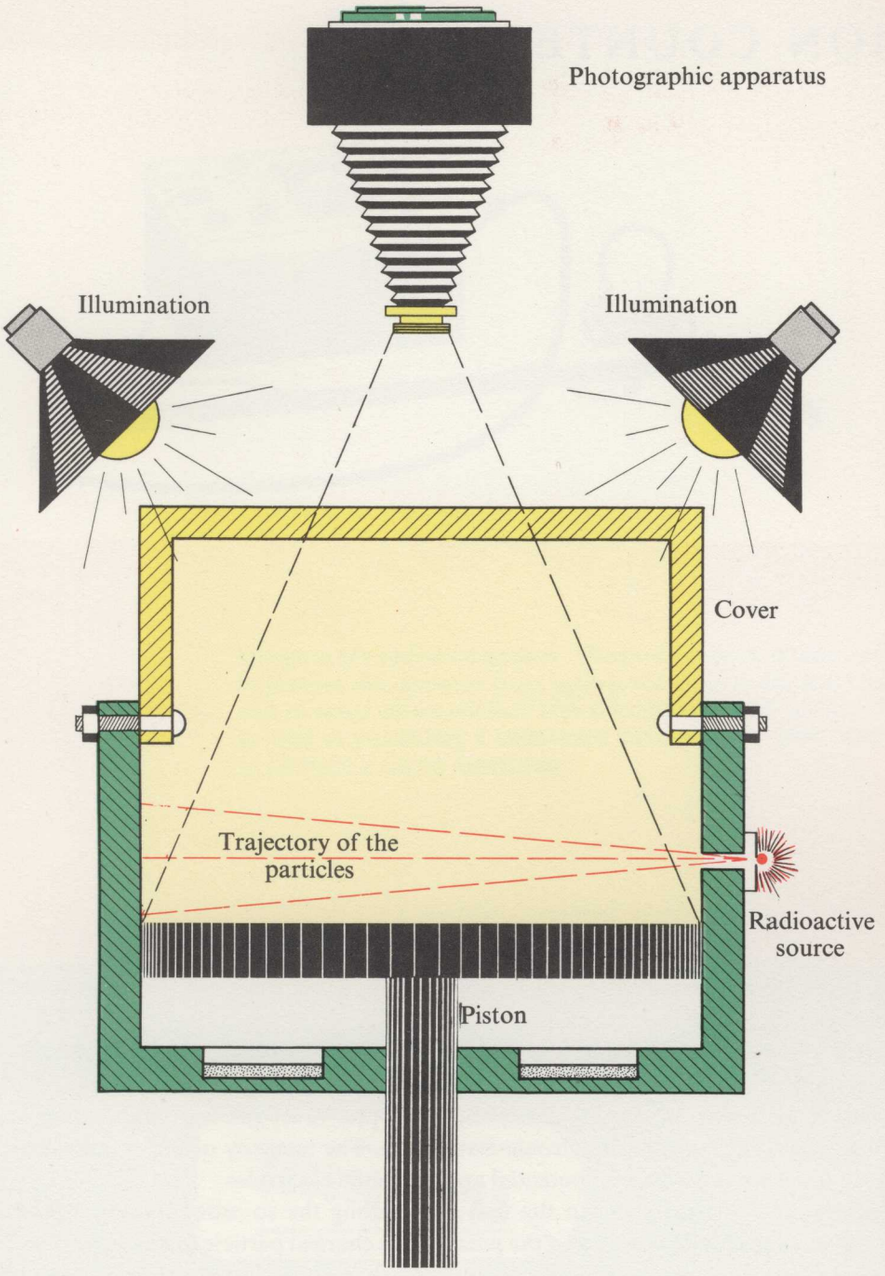
With the help of the Wilson cloud chamber (named after its inventor C. T. R. Wilson), the possibility of transmutation in elements has been unequivocally demonstrated, the neutron identified, the positron discovered, the production of positron-electron pairs by gamma rays confirmed, etc.

Besides the cloud chamber there also exists a bubble chamber apparatus for the registration of charged particles.

The principal defect of the cloud chamber, both the expansion and diffusion types, is the low density of the filling gas, so that the phenomena under observation do not occur very frequently.

In the bubble chamber, the trajectory of the particles is marked by a succession of vapour bubbles immersed in a pure liquid, similar to the drops of liquid in the fog chamber. Among fluids commonly used are liquid hydrogen, common ether, liquid nitrogen, isopentane.

The bubble chamber is very similar to the Wilson cloud chamber. Although it has certain advantages over it, it is nevertheless limited for the bubbles last a very short time (about a microsecond).



Traces or tracks of alpha particles in the Wilson cloud chamber

The piston is slowly pulled down and the gas in the metal box expands and cools, while the water vapour reaches a supersaturated state. The particles which ionize the space above the plunger break away from the radioactive source: droplets form around the ions, making the trajectories of the alpha particles, for example, clearly visible. The Wilson cloud chamber has played an important role in the study of charged particles and experimental research in nuclear physics.

The Wilson cloud chamber

GAS IONIZATION COUNTERS

The ionization chamber is an apparatus filled with a suitable gas in which ions are formed after nuclear radiation has been passed through it.

The simplest type of ionization chamber is a container filled with gas, usually air, in which two isolated electrodes are placed; often one of the electrodes is the metallic body of the chamber.

As a consequence of the passage of ionizing radiation, ions appear in the gas, causing a current which is measured with a galvanometer or other electronic instrument. The intensity of the current depends on the intensity of radiation and difference of potential applied to the electrodes.

Ionization chambers are of two types: to the first type belong the so-called impulse ionization chambers, used to measure the impulses caused by the passage of a charged particle through the chamber. To the second type belong the so-called continuous (or integration) chambers, for measuring ionization in a time interval (not too brief) or the intensity of a current caused by the passage of a group of particles through the chamber.

The various types of ionization chambers are constructed according to their purpose; impulse chambers are used to detect charged particles, especially alpha ones, while continuous chambers are used for measuring X-ray doses and obtaining data on the size of a dose of thermal neutrons.

The Geiger-Müller, or G.M., counter is also used to detect elementary particles, and was once the most commonly used device in nuclear physics research: although its use is less frequent now, it is used to detect various types of radiation and is very economical. It works on the principle of gas ionization, consequently producing impulses like the ionization chamber or the proportional counter. Here the strength or height of the impulses depends very little on the potential and not at all on the type of radiation, because in G.M. counters, the space in which ionization takes place includes almost the whole volume of the counter and thus the amplification factor assumes the highest possible value.

These counters serve to indicate the presence of radiations, but do not give information about their doses, unless the type and energy are known.

All the gas counters (ionization chamber, proportional counter, G.M. counter) work on the same basic principle, that is, they register the ionization of radiation in gas. They differ only in the potential on the electrodes, that is to say the cause of secondary ionization.

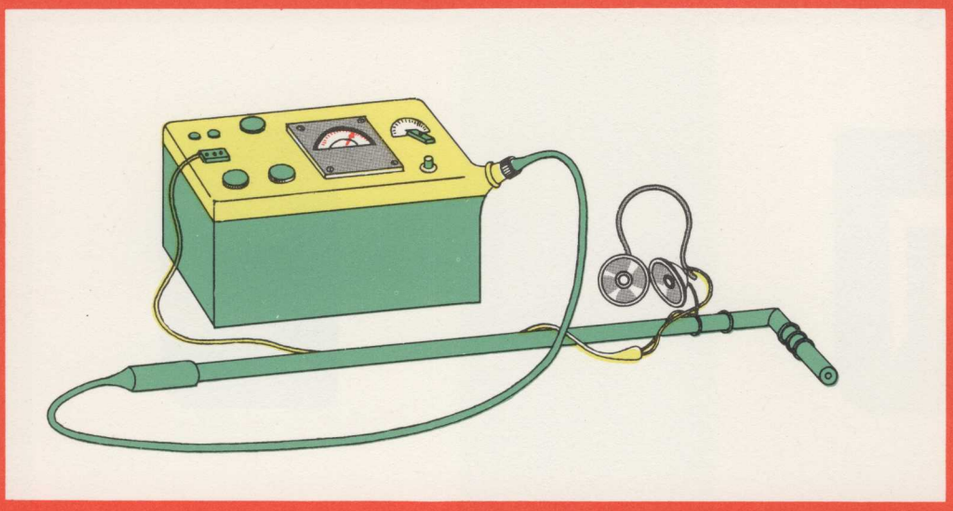
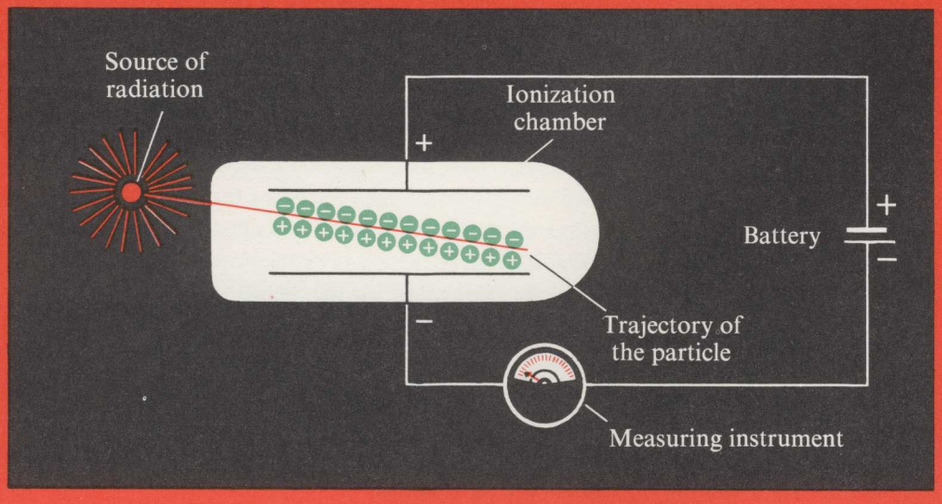


Diagram of a radiation counter. The probe counter is mounted on a handle to prevent the operator from getting too close to the source of radiation, and to avoid direct contact with the contaminated surface. The counter, as well as possessing a measuring instrument, is fitted with ear-phones to produce a sound indication.



Nuclear radiation in gas (for example in the air) situated between two electrodes produces negative and positive ions. If a potential difference is applied between the electrodes, under the action of the electric field the positive ions move towards the negative electrode and the negative ones towards the positive electrode. This phenomenon represents the so-called ionization current; it can be recorded and thus enables the intensity of the radiation to be determined. (The intensity of the current depends on the quantity of electricity carried by the ions on to the surface of the electrode in one second.)

DOSIMETERS

Dosimeters are apparatus for the detection and determination of radioactive doses. Independent of the principle on which they are based, they determine the quantity of radiation absorbed or the dose.

The dose is the quantity of radiation absorbed by an object or organism in one unit of time. Different doses exist: total dose, mortal, daily, weekly, tolerable, permissible, as a result of nuclear warfare, etc. The dose of radiation is the basic quantitative characteristic of the harmful action of radiations. Prolonged, high-intensity radiations cause illness; smaller doses absorbed at wider intervals are less harmful than radiations which are brief in time but equal in dose.

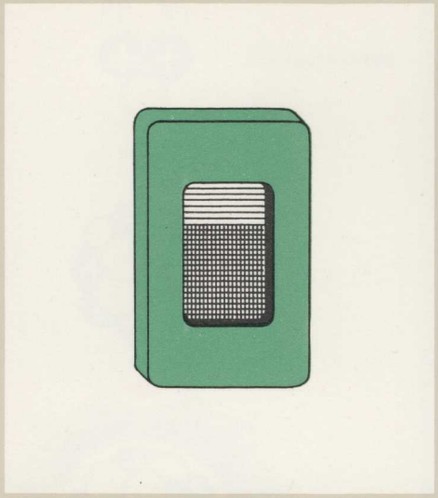
Badge dosimeter is the name given to a small meter worn as a badge on the outer surface of clothing, or as a bracelet, ring, etc. It may contain films of varying sensitivity, filters for the absorption of certain radiations and material for the registration of slow neutrons. After work, usually at the end of the week, the films are developed, and on the basis of the darkening, which is determined with the help of the dosimeter, the total dose of radiation can be read. Darkening on the photo-emulsion of the film is proportional to the dose of radiation.

Chemical dosimeter is a preparation which serves to determine the total doses of radiation on the basis of a chemical process (change of colour in some chemical materials), which occurs as a result of ionizing action. The time of exposure to radiations is calculated according to colour changes.

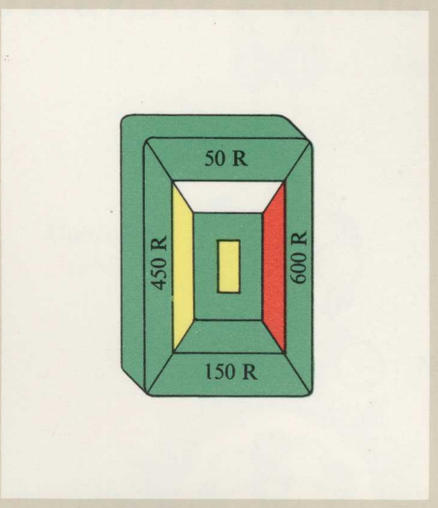
The dose can be read with the naked eye, with an accuracy of 10–15 per cent, while for doses up to 600 R it is preferable to use a special apparatus: the colorimeter.

Glass-phosphate dosimeter is the type used to measure total exposure to radiation from 10 to 600 or more R. It is very simple and economical. It consists of a square tablet of glass treated with phosphate. After exposure to radiation, this glass, when illuminated by ultra-violet light, emits fluorescence. The intensity of the fluorescence indicates the dose of radiation. These tablets are kept in small boxes of metal or plastic material and can be worn as a badge, bracelet, ring or medallion. The reading is taken with the help of a fairly complex and costly instrument: the fluorimeter.

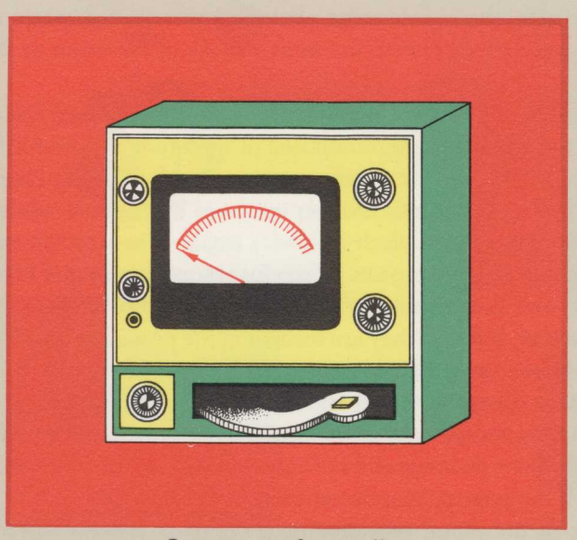
Pocket ionization chamber (pen dosimeter) is a pocket chamber with an electroscope and microscope. It is fitted with a rontgen scale which serves for direct reading of radiation doses. This dosimeter works on the principle of gas ionization. On the dosimeter scale what one actually reads is the discharge (fall in potential) which occurs with the neutralization of the ions on the electrodes, causing the indicator (quartz fibre) to move to the right. These dosimeters look like pens. To charge them with electricity, a special instrument is used.



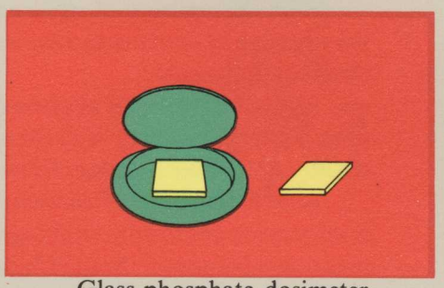
Badge dosimeter



Chemical dosimeter



Instrument for reading doses (fluorimeter)



Glass-phosphate dosimeter

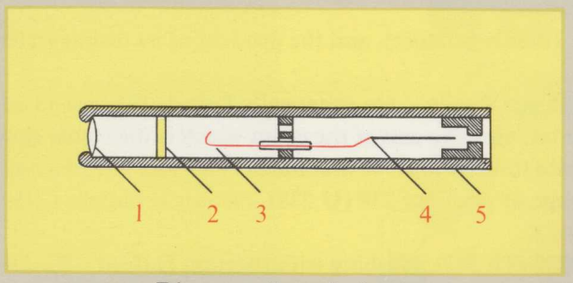
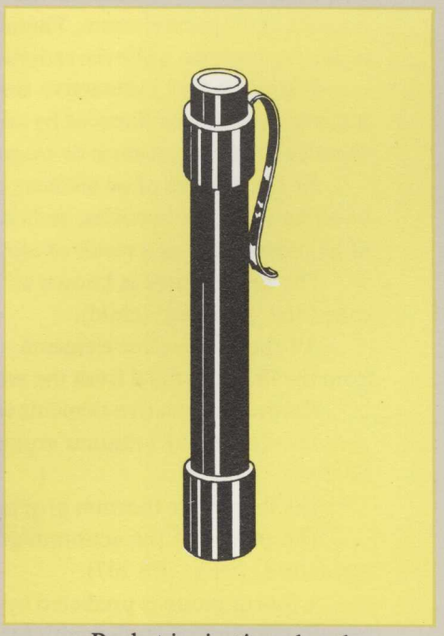


Diagram of pen dosimeter

1 – Optical system
2 – Scale screen
3 – Quartz fibre
4 – Quartz fibre electrode
5 – Tube – electrode



Pocket ionization chamber (pen dosimeter)

NUCLEAR TRANSMUTATION

Nuclear transmutation is the transformation of an atom. It occurs in nuclear reactions or in radioactive disintegration, when the number of protons in the nucleus changes.

With the emission of alpha and beta particles, the individuality of the atom is altered, while with the emission of electromagnetic waves, no charge takes place in the individuality of the atom or in its chemical properties.

With every emission of alpha or beta particles, the corresponding nucleus also changes and thus the atom concerned as well. With the emission of the alpha particle, composed of 2 protons and 2 neutrons, the atomic number decreases by two units (2 protons), and the atomic mass number by 4 (4 particles).

With the emission of the beta particle (electron), the atomic number increases by one unit, while the mass remains practically unchanged because the mass of the electron is very small. (The electron leaves the nucleus because of the transformation of a neutron into a proton.) Therefore an extra proton is formed in the nucleus, increasing the atomic number, and thus forming the nucleus of another element. This means that there are no beta particles in the nucleus, but that they are formed in the process of this transmutation in the nucleus itself and leave the nucleus immediately.

With the emission of gamma rays, there is no change in the atomic number or, practically speaking, in the mass of the nucleus; inside the nucleus a rearrangement of the nucleons occurs, but the nucleus remains of the same element. Therefore the radioactive disintegration of the atom is a change which occurs inside the nucleus, while the radiation emitted is the external manifestation of these changes.

The course of radioactive disintegration in the atom, representing a complex process inside its nucleus, cannot be influenced by any means yet known to us or within our control (temperature, pressure, chemical methods, electric or magnetic fields, etc.).

As the nucleus of an element is transformed into the nucleus of another element with the emission of alpha and beta particles, radioactive families of atomic nuclei are formed, each nucleus being born of its predecessor as a result of alpha or beta disintegration.

The first element is known as the 'parent' (family founder), and the product of its disintegration is called the 'daughter' (child).

All the radioactive elements – members of one family – are genetically linked: the second comes from the first, the third from the second and so on, until the end of the chain which is the stable isotope.

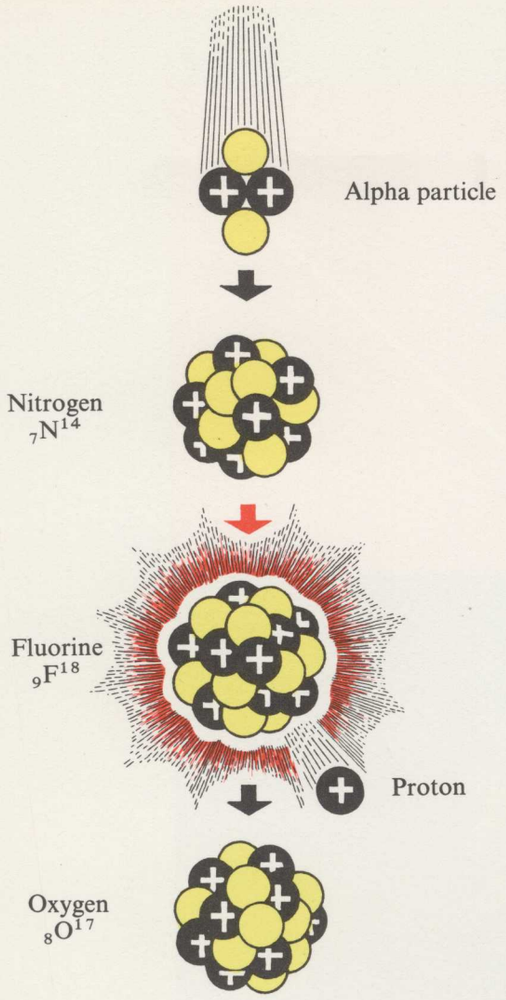
Natural radioactive elements are divided into three groups: of uranium, of thorium and of actinium.

The first in the uranium group is the isotope of uranium 238 (U 238), the last is radium G (lead – Pb 206).

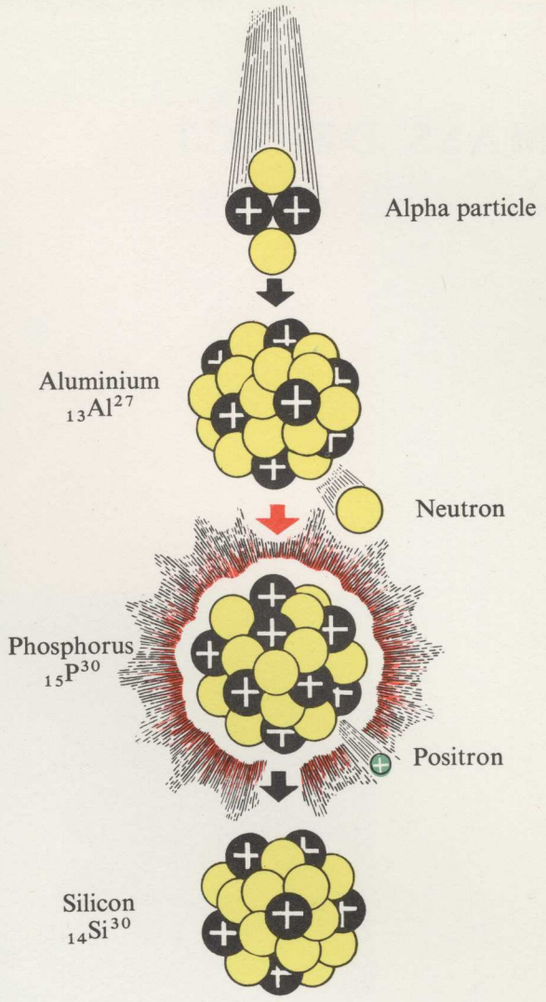
The first in the thorium group is thorium 232 (Th 232), finishing with thorium D (lead – Pb 208).

The parent of the actinium group is the so-called actinium uranium 235 (AcU 235), ending with actinium D (lead – Pb 207).

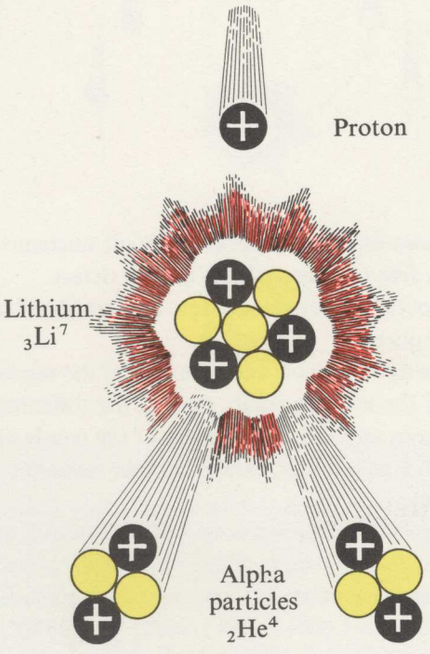
A fourth group is predicted by science and takes its name from the member with the longest half-life period, neptunium, ending with the stable isotope of bismuth 209 (Bi 209). Its descendants are produced artificially in nuclear reactions. The members of this group have such brief half-lives in relation to geological time that they are not found in nature.



When an alpha particle enters the nucleus of nitrogen it transforms it to an atom of fluorine which on disintegration becomes the nucleus of oxygen, releasing a proton. In this way scientists first succeeded in transforming a nitrogen atom into an oxygen atom – that is, one chemical element into another.



If an aluminium atom is bombarded with alpha particles, the aluminium is transformed first into radioactive phosphorus and then into silicon.



If a proton penetrates an atom of lithium 7, the atom is transformed into two alpha particles.

MASS DEFECT

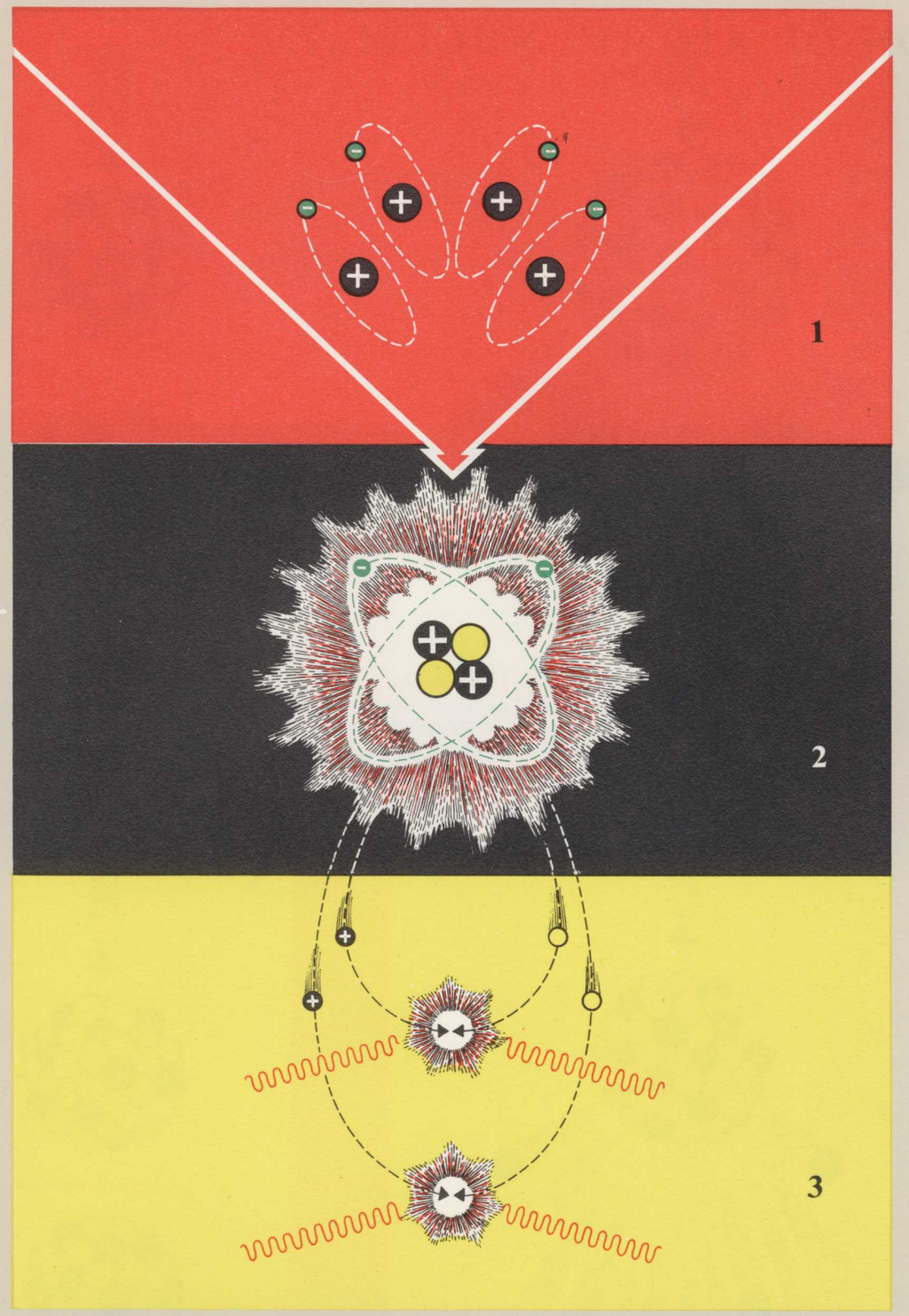
The mass defect is the total loss of mass undergone by all nucleons joining together in the nucleus. The formation of a nucleus by free nucleons causes a mass defect.

To split up the nucleus into its component nucleons, a quantity of energy equal to that corresponding to the mass defect must be supplied.

Thus the mass defect is the difference between the sum of the masses of the particles constituting the nucleus and the total mass of the nucleus itself; that is, the difference between the atomic masses of the particles constituting an atom and the atomic mass of the whole atom.

When a nucleus is formed, a part of the nucleon's mass 'vanishes'. This phenomenon is clarified by the example of the alpha particle.

The mass of the alpha particle corresponds to 4·00280 atomic units of mass and is composed of protons having masses of 1·00813 atomic units of mass and of neutrons having masses of 1·00895 atomic units of mass. Given that an alpha particle is composed of 2 protons and 2 neutrons, the sum of the masses of these 4 particles will be $2 \times 1{\cdot}00813 + 2 \times 1{\cdot}00895 = 4{\cdot}03416$. The mass defect is the difference between this sum and the mass of the alpha particle; this difference is 0·031 atomic units of mass. On the basis of the Einstein relationship between mass and energy, it is found that an energy of about 28 MeV corresponds to this mass. Therefore, for each nucleon in the atomic nucleus of helium an average of 7 MeV is lost; thus, the loss of mass in a nucleus, corresponds to an exact quantity of energy (bond energy).



Between the particles of an atomic nucleus exists a binding energy of several MeV per nucleon. It has been shown that the sum of the masses of protons and neutrons of a nucleus is greater than the mass of the nucleus itself. This phenomenon of inequality of mass between a body and its parts is called the mass defect. The binding energy of bond differs in various elements. With the fission of heavy nuclei or the fusion of light nuclei, a part of the energy of the nucleus is released. This energy, which is then nuclear energy, is calculated on the difference of total mass, before and after reaction.

The diagram illustrates mass defect. From 4 hydrogen atoms (1) a helium atom can be formed (2). A second possibility is the formation of 2 deuterium atoms (3). Here the mass defect is less, and about 4 MeV of energy is released, 2 for each deuterium nucleus. This energy, which corresponds to the mass defect, is released with the radiation.

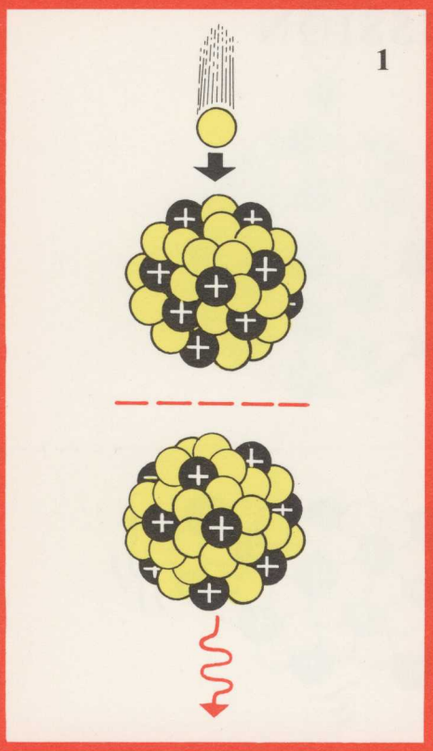
FISSION OF ATOMIC NUCLEI

The fission of atomic nuclei is the process in which the atomic nucleus of a heavy element breaks up, either spontaneously or as a result of bombardment with neutrons or other particles, into two almost equal fragments. Fission into three fragments (the third is very often an alpha particle) or into four occurs very rarely – into three once in every 500 cases, and into four once in 3,000 cases.

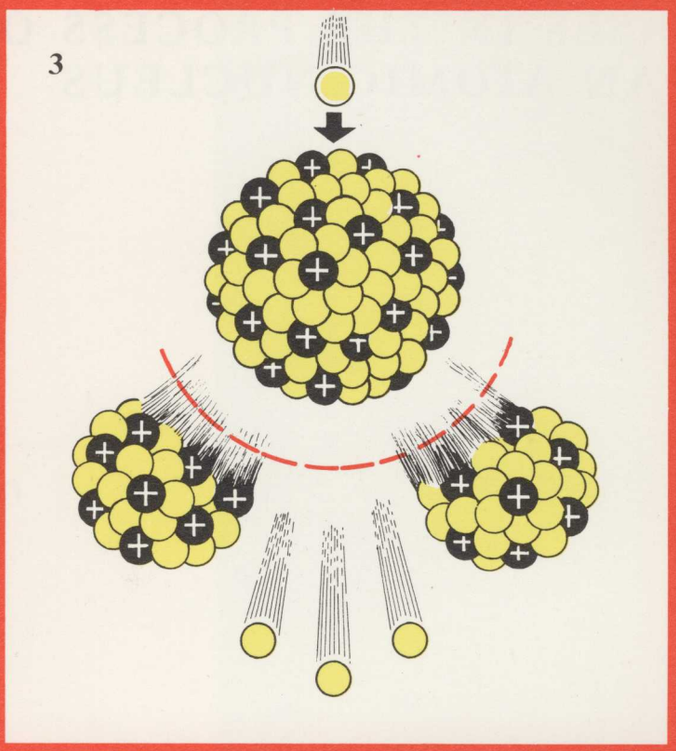
Fission induced by neutrons has a practical significance. However it can also be induced by means of particles, deuterons, gamma waves, etc.

Fission fragments of heavy atomic nuclei possess a marked excess of neutrons and are unstable; before transforming themselves into stable nuclei they give rise to a chain reaction of beta disintegrations. In fission, besides the fragments, neutrons and gamma rays are also emitted.

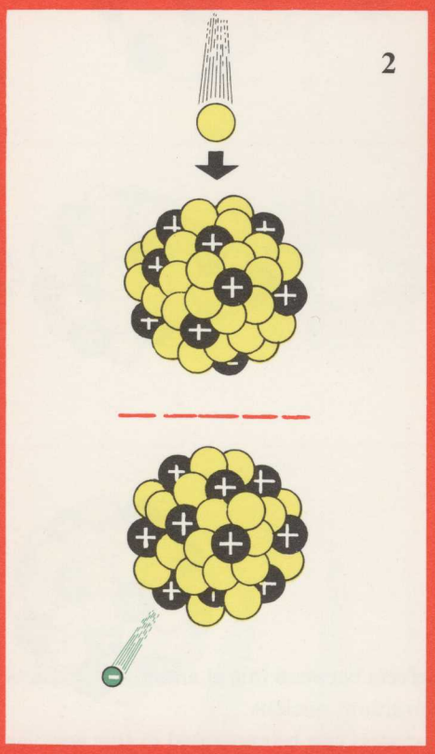
Energy released in the fission of a heavy nucleus reaches about 200 MeV. Eighty per cent of this energy is kinetic: the fragments of fission spread at a speed of about 10,000 km/sec.



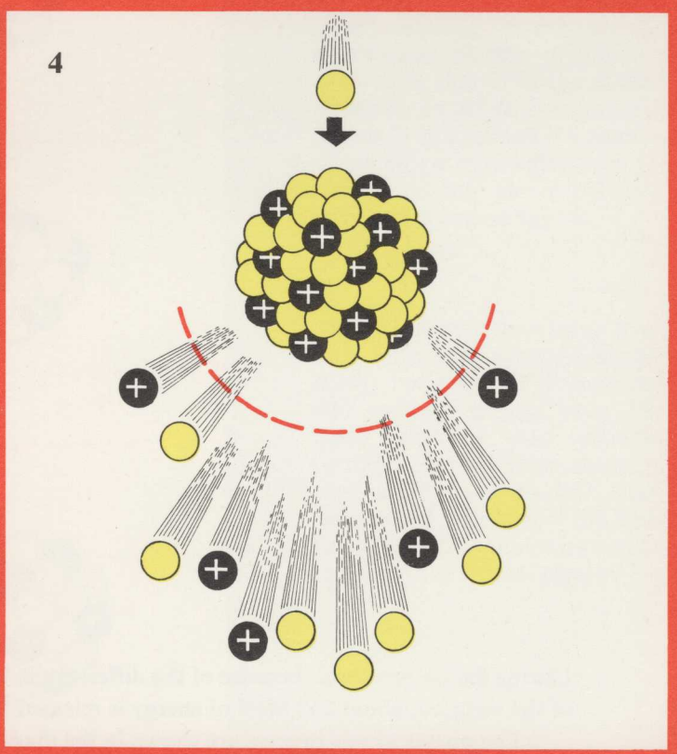
When a neutron penetrates the nucleus and is absorbed, there is a possibility that the nucleus will not change but simply emit a gamma ray. This process is called radioactive absorption.



When a neutron penetrates the nucleus and is absorbed, the neutron may be transformed into a proton; an electron leaves the nucleus and the new nucleus acquires an extra proton.



When a neutron penetrates the atomic nucleus of uranium 235, the nucleus splits into two equal fragments, with the release of 2–3 neutrons and energy.



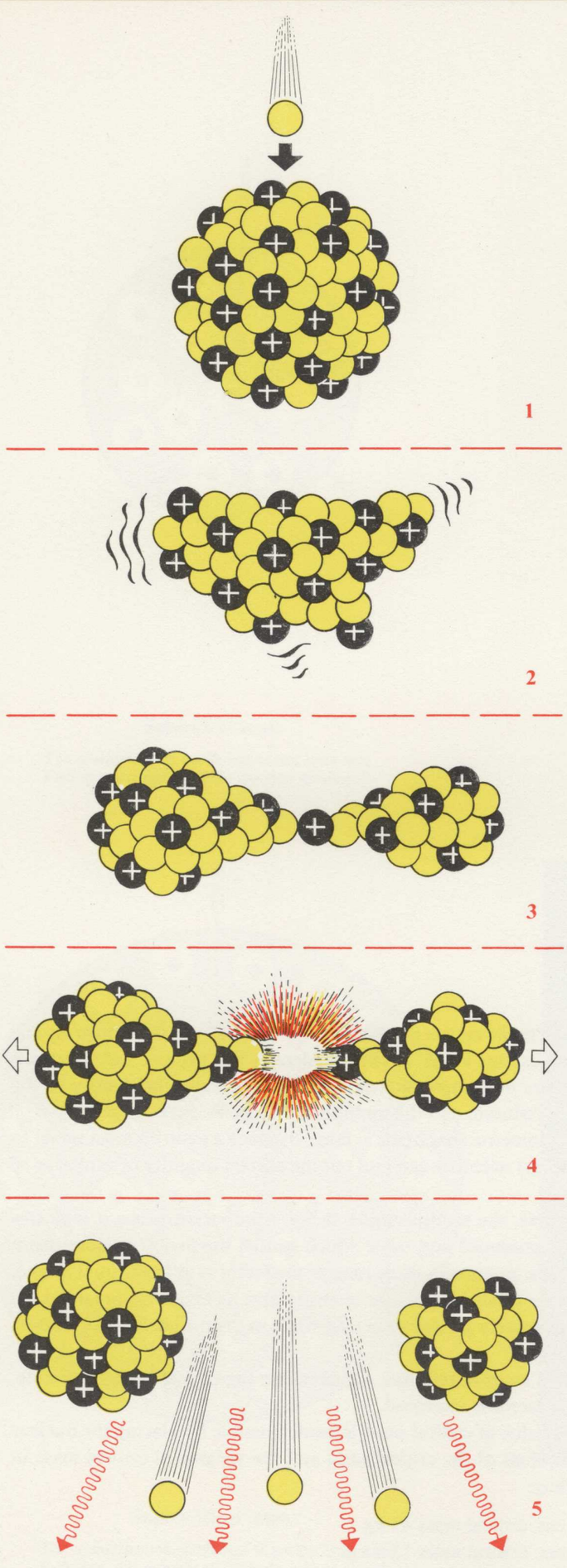
When a high-energy proton from cosmic radiation collides with a nucleus, it may break it up into fragments.

Diagram of possible processes in collisions between neutrons and the nucleus of uranium

PHASES IN THE PROCESS OF FISSION IN AN ATOMIC NUCLEUS

During fission processes, because of the difference in the mass defects between initial and final products of the reaction, about 200 MeV of energy is released from each uranium nucleus.

The phases of this process are shown in the diagrams. The process can be explained in this way: as a model of the nucleus we may take a water drop where all the particles are kept together by a cohesive force; if a particle of a certain kinetic energy falls into this, a new system is created, which takes on a different energetic state; it begins to tremble, changes shapes, returns to the primitive state and vibrates. If the frequency of this vibration is near or equal to the natural oscillation frequency of the new system, it may break up into fragments.



When a neutron enters the nucleus of uranium 235 for example (1), an unstable nucleus of uranium is formed, that is in the excited state (2). In about one hundred millionth of a second it elongates in the shape of a water drop (3) and breaks into two equal fragments releasing energy (4).

The fragments move away from each other with a certain kinetic energy, releasing 2–3 neutrons and emitting gamma rays. The freed neutrons may provoke further fission of other nuclei in such a way that nuclear chain reaction (5) develops, if the mass has a certain minimum value, known as the critical mass.

Phases in the process of fission in an atomic nucleus

CRITICAL MASS

The critical mass is the minimum quantity of fissile matter in which a chain reaction can develop in atomic nuclei. The critical mass does not have an absolute value: the purity, density and geometrical shape can modify its size considerably. Under pressure or compression, known as implosion, the density of the fissile matter can be increased, its diameter reduced, and the multiplication coefficient enlarged.

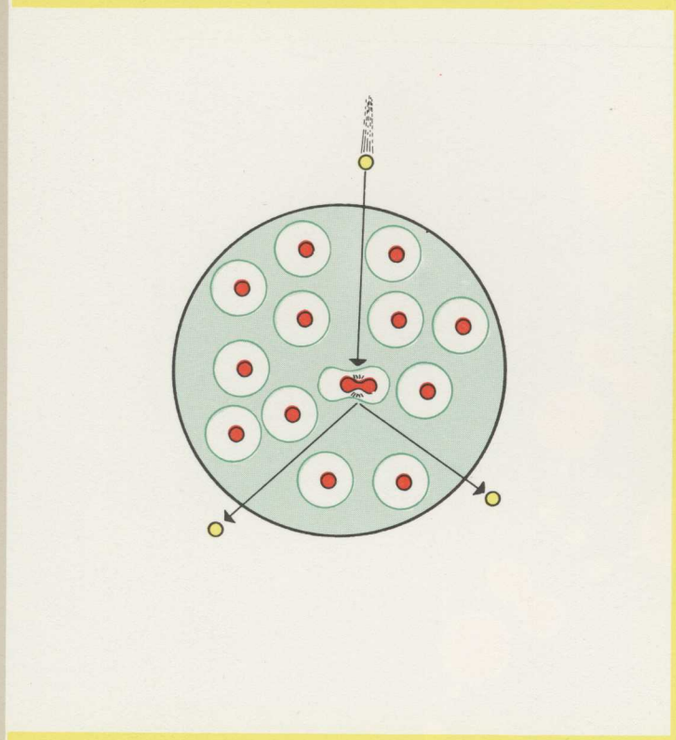
By regulating the purity, density and geometric shape (the average distance a neutron must travel to provoke fission in a nucleus is less than 10 cm) scientists can find out the correct quantity of explosive to put in an atomic weapon.

To keep the nuclear chain reaction alive, the multiplication factor is important since it indicates the ratio between the number of neutrons produced and those which caused the fission reaction from which they were created. Chain reactions can continue only as long as the factor is at least equal to one. The size of this factor indicates the increase of chain reaction intensity and its explosive potential. In uncontrolled fission (an atomic bomb) it is notably greater than one, while in controlled fission (reactor) it is very near to one.

If the fissile material is surrounded by a neutron reflector, a decrease in the critical mass is possible, because in this way the neutron utilization factor is increased.

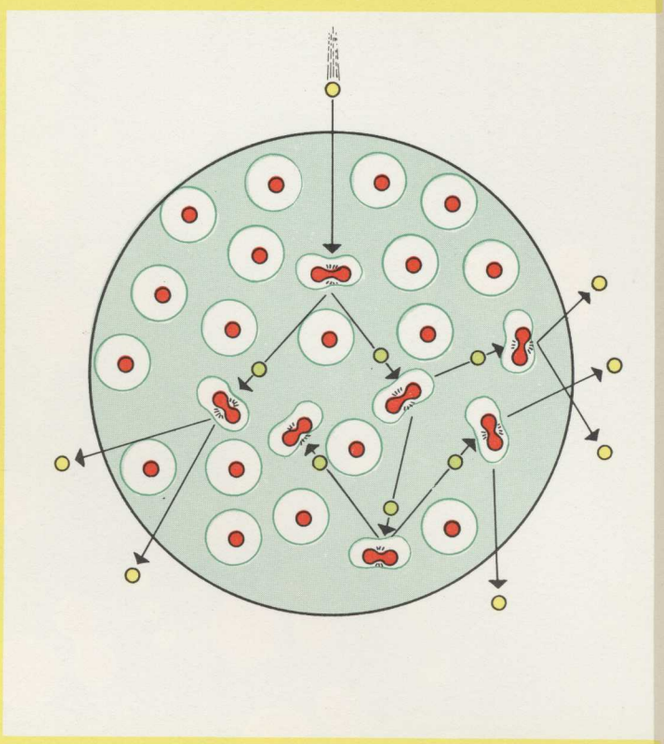
In nuclear weapons, a decrease in the value of critical mass is made possible by placing the nuclear explosive inside a neutron-reflector. The values of the critical radii and the weights of critical mass in atomic explosions have been calculated thus:

Uranium – 235: critical radius 8·4 cm, critical mass 45 kg.
Uranium – 233: critical radius 5·6 cm, critical mass 13·6 kg.
Plutonium – 239: critical radius 5·0 cm, critical mass 10 kg.



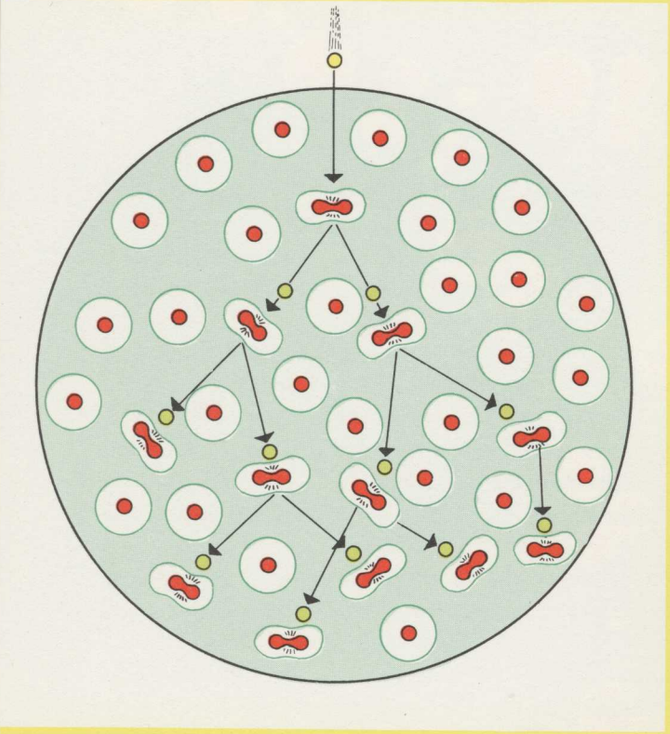
Subcritical mass

The multiplication coefficient is less than one.
Fission starts but no chain reaction develops.



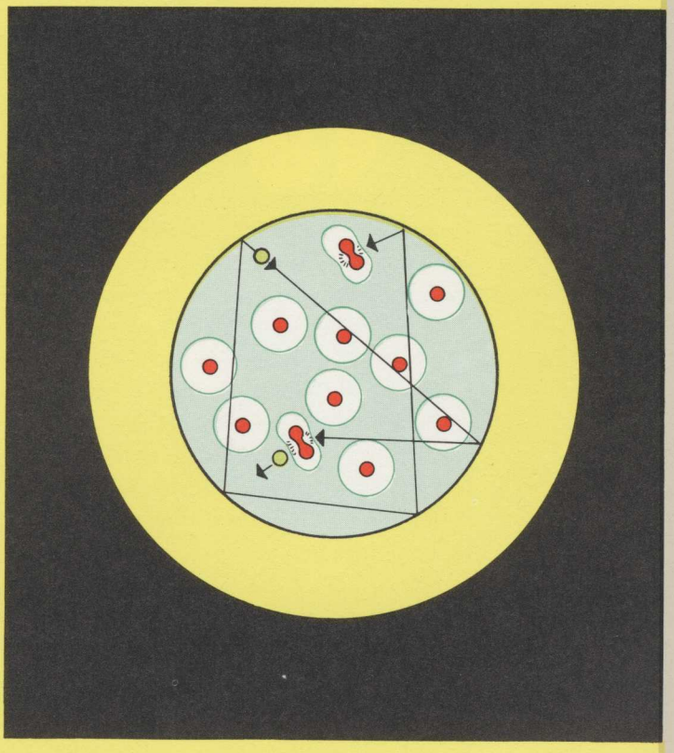
Critical mass

The multiplication coefficient is one.
From each fission a neutron is created with a capacity for further fission.



Supercritical mass

The multiplication coefficient is greater than one.
In fission, the number of neutrons and of fissions increases in geometrical progression.



Critical mass with neutron reflector

When the fissile material is surrounded by a neutron reflector, chain reaction can develop, even where the mass is initially subcritical.

CHAIN REACTION IN FISSION

Chain reactions are nuclear and chemical processes which, once started, continue to develop, extending without external stimuli to the whole mass of molecules, atoms or nuclei concerned.

Chain reactions constitute a particular type of chemical, photochemical or nuclear reaction. In the first elementary process, intermediate products are formed (free radicals, molecules, atoms, neutrons, etc.), which in turn cause new reactions, giving new molecules, atoms or nuclei.

In a chain reaction in the atomic nuclei of heavy elements caused by neutrons, a neutron provokes the fission of the nucleus; in this process new neutrons are created, which can cause the fission of other nuclei. From one neutron which started the reaction, the process continues without external stimuli.

These reactions liberate energy. Chain reactions are based on the fact that the ratio between the number of neutrons and the number of protons in the uranium nuclei is greater than in the fragments of fission; therefore in the fission of atomic nuclei of uranium, some neutrons are released capable of continuing the reaction.

How is chain reaction primed in atomic weapons? A neutron produces the first fission of the nucleus. The first neutron may come from cosmic radiation, from the spontaneous fission of a nucleus, or from the neutron source placed in the atomic weapon.

It is highly probable that a chain reaction will start if the critical mass is exceeded. It is known that, in every fission process, 2–3 neutrons are released. Supposing that the two new neutrons always cause further fission (not all the neutrons produced cause fission) it is evident that in a chain reaction, the number of neutrons will always increase.

For example, after the first fission there will be 2 neutrons, from these 4, then 8, 16, 32, 64, 128, 256, 512, 1,024, 2,048, etc., until in the eightieth generation (every number represents a generation) there will be a billion billion neutrons (10^{24}).

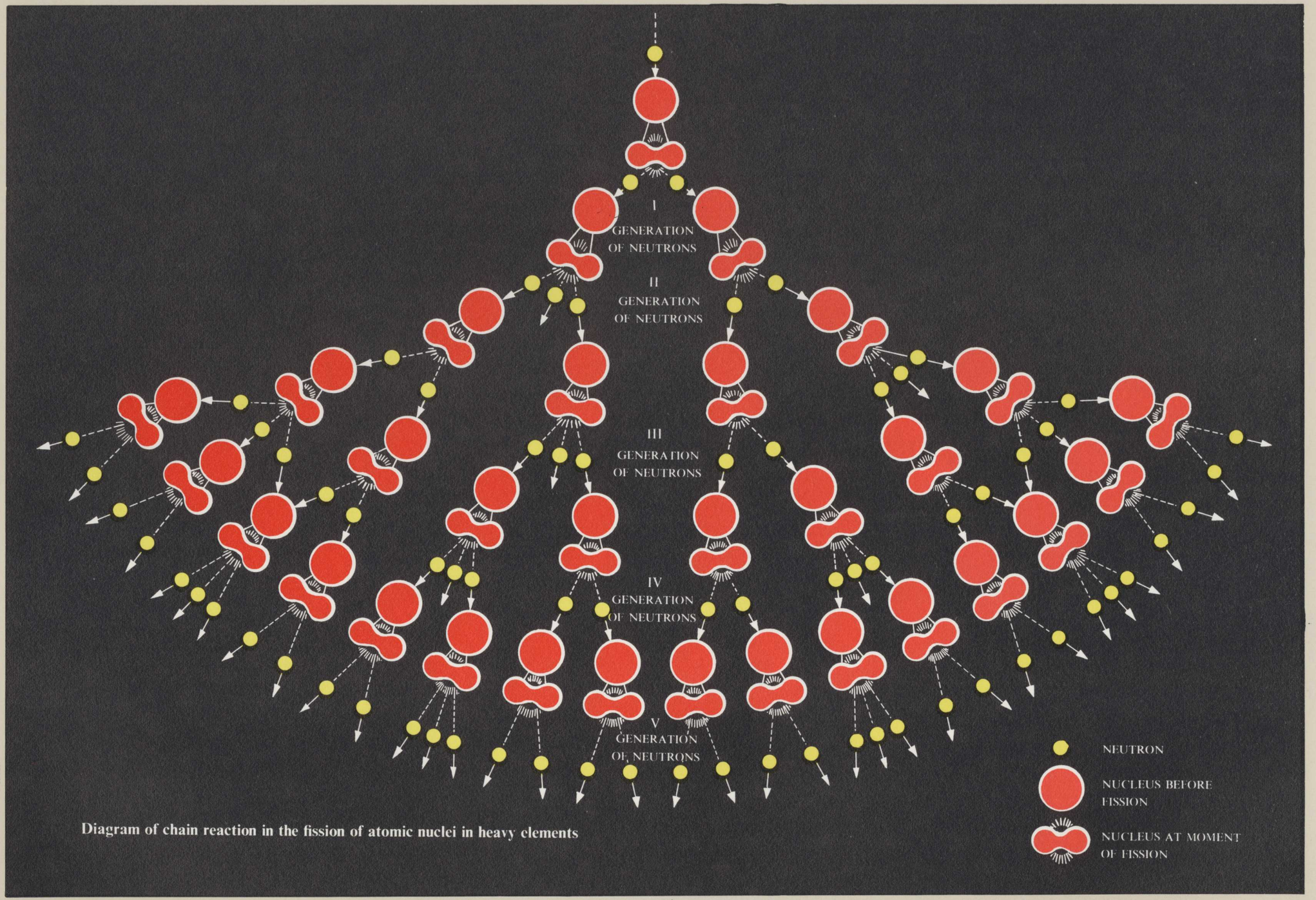


Diagram of chain reaction in the fission of atomic nuclei in heavy elements

ENERGY RELEASED IN THE FISSION OF THE ATOMIC NUCLEUS

The approximate subdivision of energy released in the fission of an atomic nucleus is shown in the table beneath the diagram. In reality this energy represents a part of the binding energy – that is, part of the difference between the energy belonging to the united state of the particle system, and the energy belonging to the separated state in which the particles move away from each other.

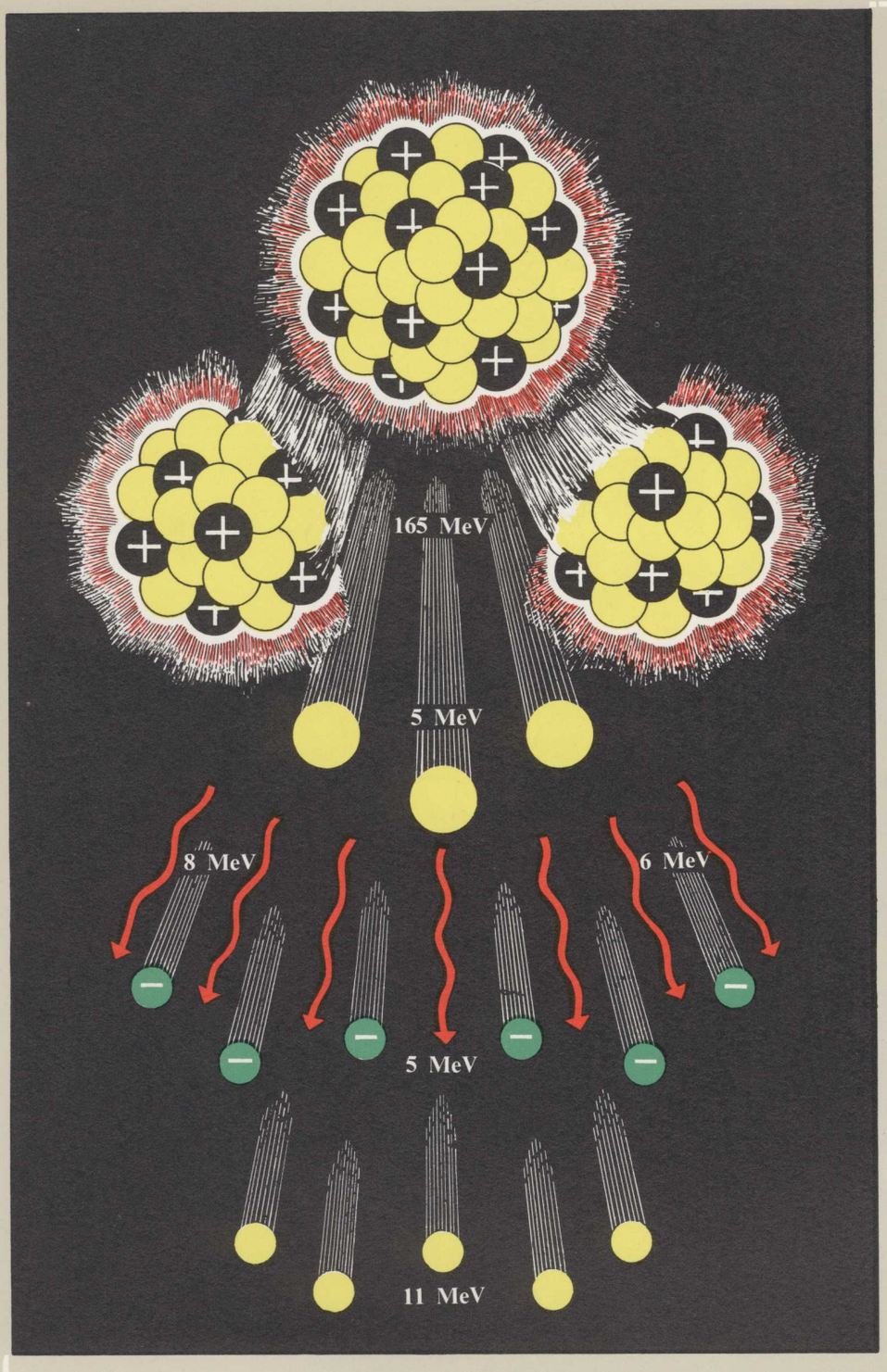
The energy involved in forming the molecule is that of chemical bondage; but if it is involved in forming the nucleus of the atom, then the energy is that of the nuclear bond (there are also other forms of binding energy). This energy corresponds to the work necessary to divide the system into its components.

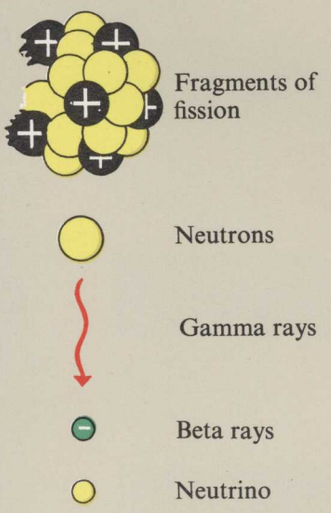
The binding energy of the atomic nuclei amounts to millions of eV; this explains the exceptional stability of the atomic nuclei. The binding energy of the deuteron for example, composed of one proton and one neutron, is equal to 2·2 MeV, while the binding energy of the uranium atom is about 1,780 MeV.

Thus if we unite 92 protons with 143 neutrons in the nucleus of uranium 235, we obtain 1,780 MeV. In the fission of the U 235 nucleus, not all of this energy is released, only that part of the binding energy which is the difference between the masses of the U 235 nucleus and the masses of the fission products. This difference is about 200 MeV.

The electronvolt (eV) represents in physics a unit of energy, and corresponds to the energy acquired by an electron accelerated by a difference of potential of one volt.

This unit of energy is applicable both to other particles and to photons (1 eV = $1{\cdot}60 \times 10^{-12}$ erg.). Larger units are keV (kiloelectronvolt = 1,000 eV) and MeV (Mega-electronvolt = 1,000,000 eV).





In the fission of the atomic nucleus, 200 MeV of energy is released, distributed in this way:

Kinetic energy of fission fragments	165 MeV
Kinetic energy of neutrons	5 MeV
Energy of instantaneous gamma radiation	8 MeV
Energy of beta decay in fission fragments	5 MeV
Energy of gamma decay in fission fragments	6 MeV
Energy of neutrino	11 MeV

Energy released in the fission of the atomic nucleus

FISSION FRAGMENTS OF ATOMIC NUCLEI

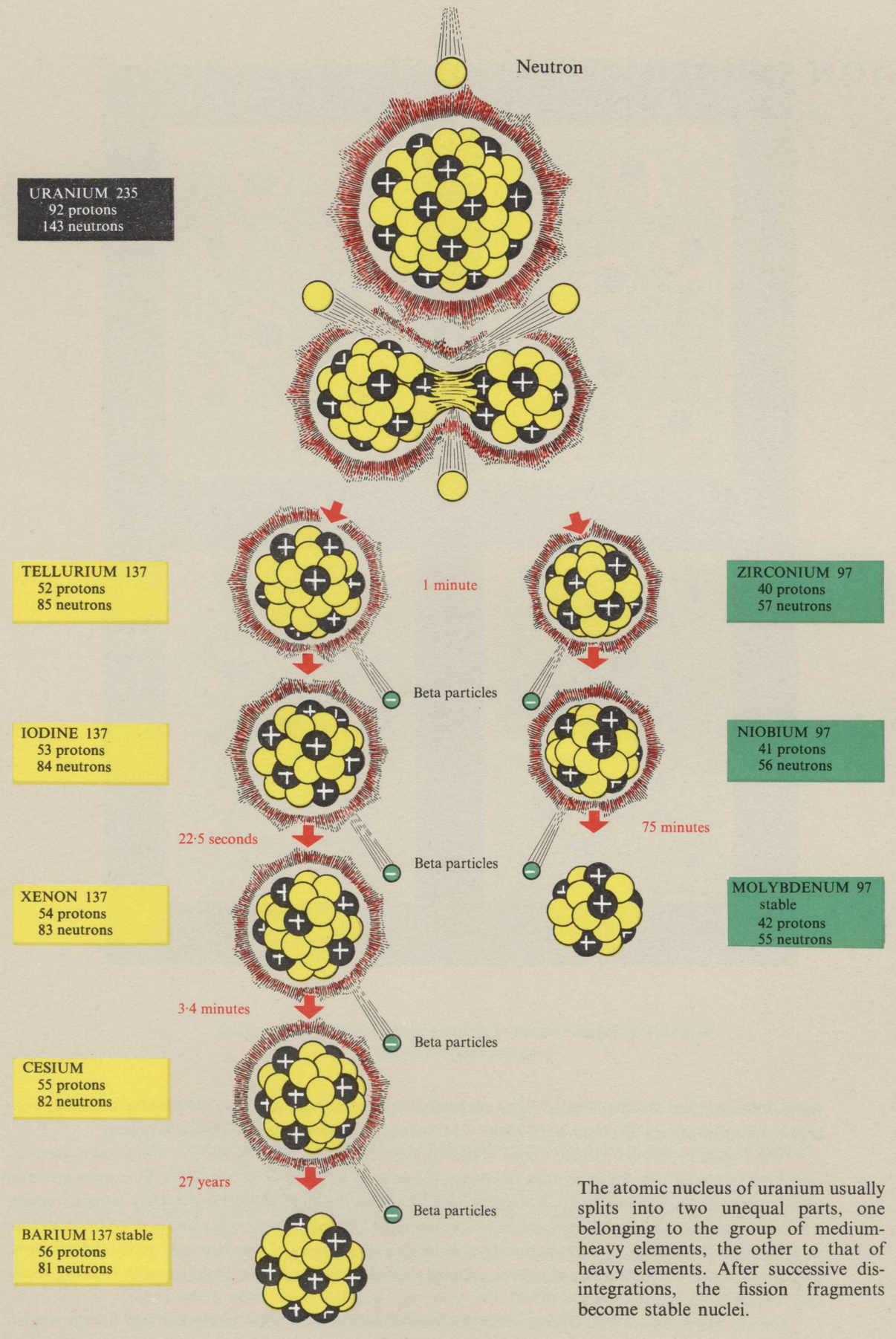
Fragments are the particles into which the atomic nuclei disintegrate in the fission process, or rather they are the new atomic nuclei formed in the fission process.

Normally the nucleus of a heavy atom splits into two asymmetrical parts: one part belongs to the group of medium-heavy elements, with a number of mass around 90, and the other to that of the heavy elements, with a number of mass around 180.

The atomic mass numbers of the fragments range from 72 to 158; there are about 34 different isotopes.

The fragments possess great kinetic energy, about 80 per cent of the energy released is fission. They also have a large neutron excess, and before transforming to stable nuclei, they undergo beta disintegrations.

The diagram shows the fission of the uranium 235 nucleus, the formation of fragments and their disintegration to the point where they become stable nuclei.



The atomic nucleus of uranium usually splits into two unequal parts, one belonging to the group of medium-heavy elements, the other to that of heavy elements. After successive disintegrations, the fission fragments become stable nuclei.

Fission fragments of atomic nuclei

FUSION OF ATOMIC NUCLEI

By fusion we mean the synthesis of light nuclei and heavier atomic nuclei. This process occurs at very high temperatures, not less than 10,000,000° C; it takes the name of thermonuclear reaction.

The fusion process in atomic nuclei is the opposite of fission; during fusion, which takes place at very high temperatures, an enormous quantity of energy is released. The heavy nuclei cannot give rise to this type of reaction, as it is not known how to create the high temperatures they would require. The necessity for such a high temperature derives from the fact that in fusion the nuclei must be very close to each other in order to overcome considerable electrostatic forces of repulsion. At such temperatures, the light elements are in the state of plasma, and the particles carry sufficient kinetic energy to bring about their fusion.

Fusion reactions are well documented for the nuclei of tritium and deuterium into helium nuclei, in which a neutron and energy of 17.6 MeV are freed; similarly a lot is known about the reaction of fusion in lithium and deuterium, in which energy of 22.4 MeV is released.

In this way, from 1 kg of a thermonuclear fuel about 50–100,000,000 kWh of energy can be released.

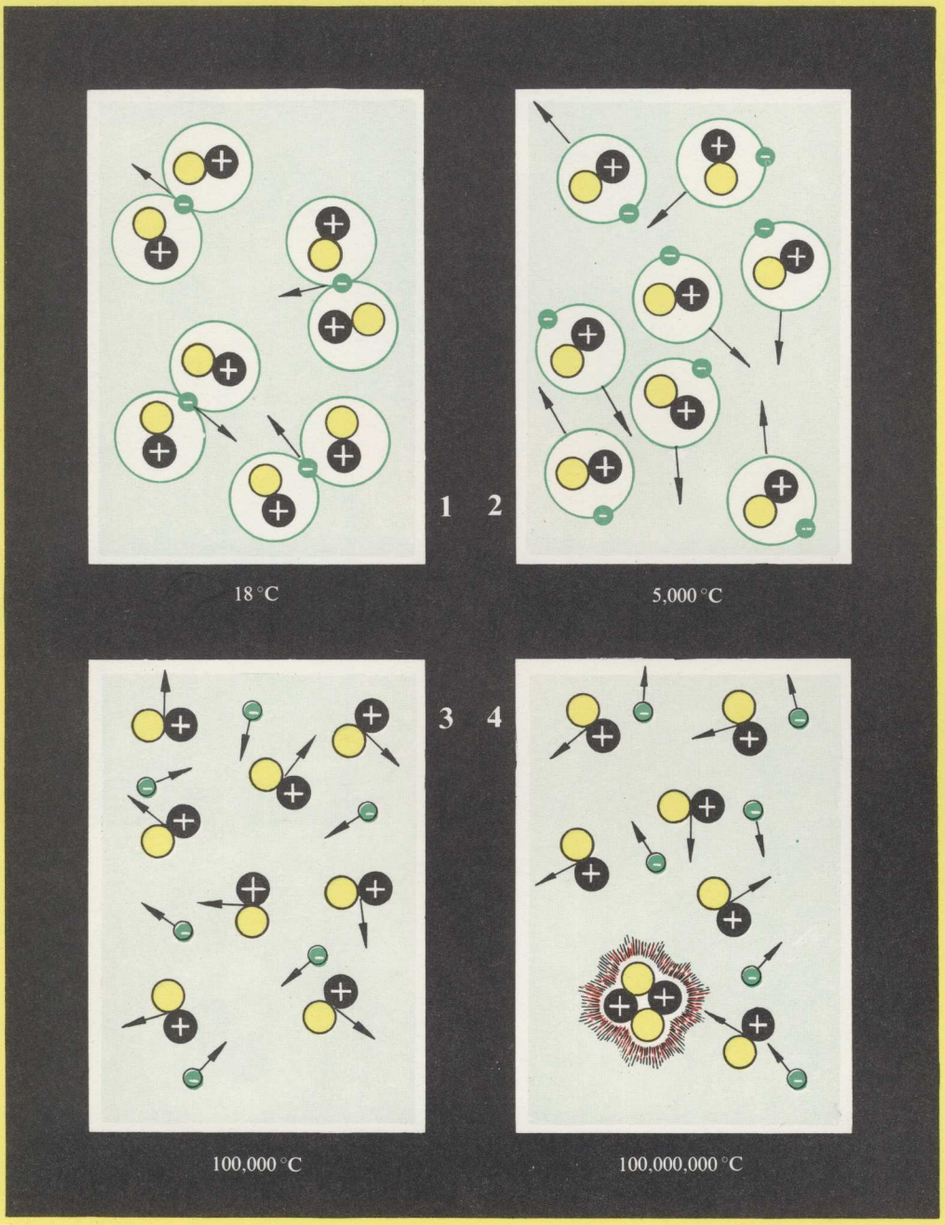


Diagram of various fusions possible in atomic nuclei of hydrogen and deuterium isotopes

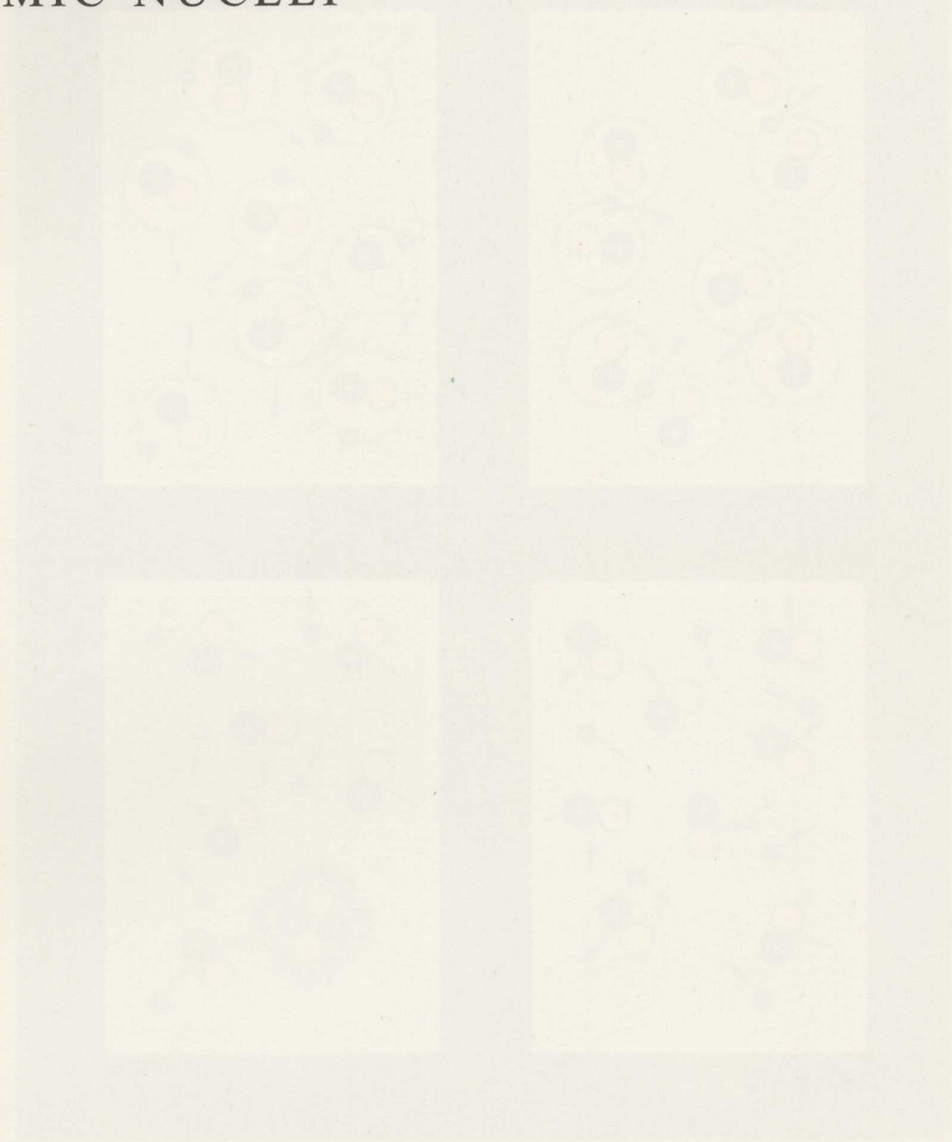
1 At environmental temperature and normal atmospheric pressure, deuterium is in the molecular state.

2 At a temperature of 5,000°, deuterium molecules split into atoms, while pressure increases to 40 atmospheres.

3 At a temperature of 100,000°, deuterium atoms break up, and plasma is formed while pressure rises to as much as 1,500 atmospheres. The matter is in an ionized state – naked atomic nuclei and free electrons are subject to intense thermic motion.

4 At 100,000,000°, the speed of deuterium ions becomes high enough to overcome electrostatic repulsion among them; thus starts the process of thermonuclear fusion. It is not a chain reaction and dies out. The thermonuclear fusion of isotopes of hydrogen, deuterium and tritium, begins around 4–5,000,000°.

PHASES IN THE PROCESS OF FUSION OF ATOMIC NUCLEI



The diagram illustrates schematically the fusion process of atomic nuclei of isotopes of hydrogen, deuterium and tritium into a nucleus of helium. In this process a neutron and 17·6 MeV of energy are released.

To fuse two nuclei of the same chemical element or of different chemical elements, it is necessary to create the conditions of a violent collision between them; this may occur only when the nuclei travel at enormous speeds, and these can be obtained at very high temperatures.

When the atoms free themselves of their electrons (electron clouds), leaving the respective nuclei naked, strong repulsive action occurs between them; thus enormous speed is needed to overcome the force of electrostatic repulsion, causing first collision and then fusion.

These processes are possible only in light nuclei; in heavy ones carrying a larger number of protons, it would be necessary to overcome still greater forces of repulsion and thus to have even higher temperatures available.

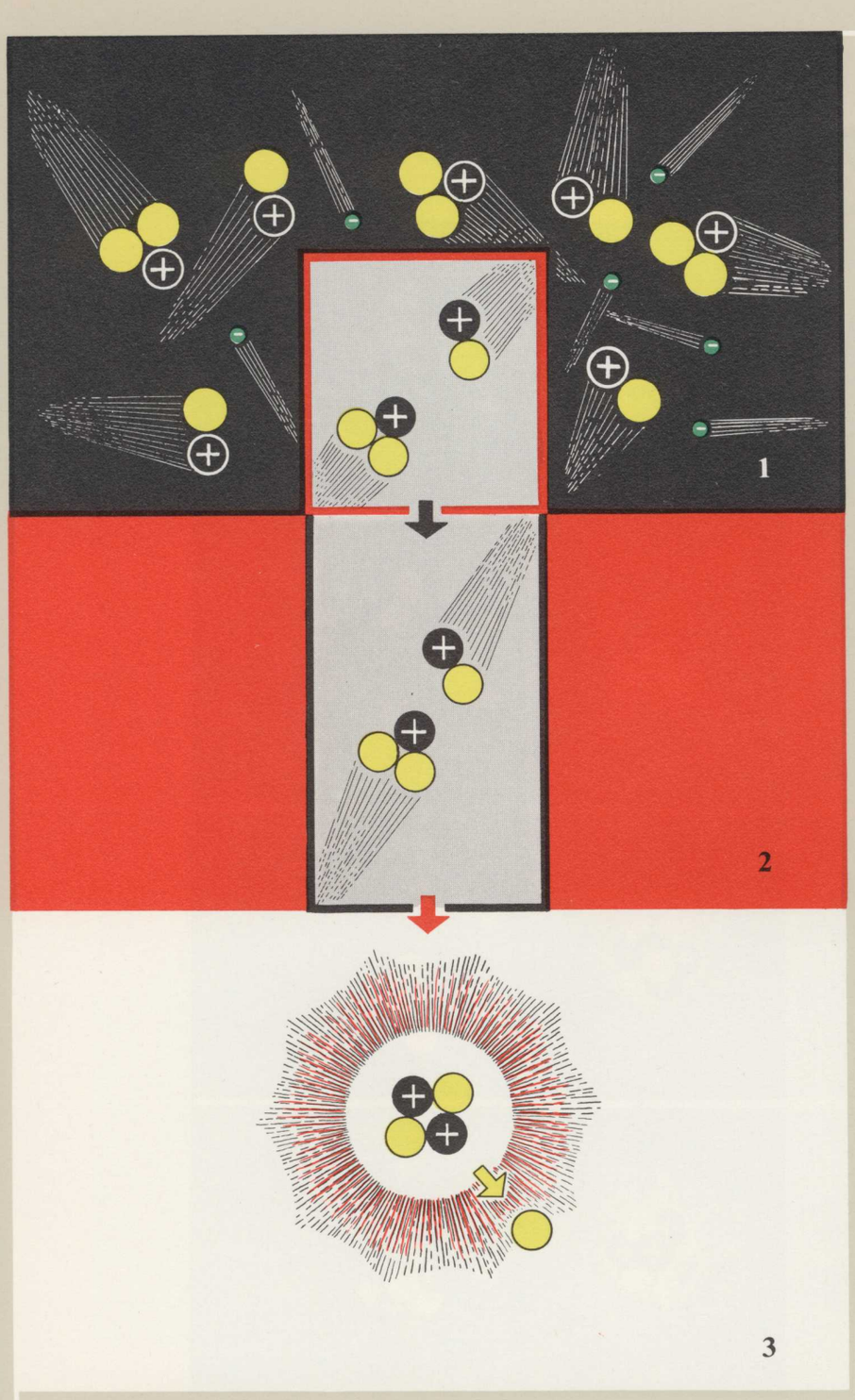


Diagram of the fusion process of atomic nuclei

Nucleus of the atom of deuterium

Nucleus of the atom of tritium

Nucleus of the atom of helium

Neutron

Electron

1 The fusion of atomic nuclei is possible only at high temperatures. At very high ones the atoms lose their electrons which continue to move freely among the remaining naked nuclei.

2 For fusion to occur, the nuclei must be brought very close together. As they carry a positive charge, great speed (kinetic energy) is required to overcome their repulsive action.

3 Among the various thermonuclear reactions possible, one of the best known is that of the fusion of the nuclei of hydrogen, deuterium and tritium isotopes into the nucleus of helium – a neutron is freed and 17·6 MeV of energy released.

Phases in the process of fusion of atomic nuclei

ENERGY RELEASED IN THE FUSION OF ATOMIC NUCLEI

The diagram illustrates some thermonuclear reactions of fusion in lightweight atoms and the energy released.

As we have already said, there is a close connection between mass and energy; energy may be released in various reactions. For example, in chemical reactions, the combustion of 1 kg of naphtha releases 11·6 kWh of energy.

In nuclear fission reactions in the nuclei of 1 kg of uranium, 22·9 million kWh of energy are released. In thermonuclear reactions, the fusion of 1 kg of hydrogen into helium, releases 177.5 million kWh of energy.

It is thermonuclear reactions which have the greatest thermal effect. As a product, they give nuclei of the helium atom ($^{4}_{2}H$) in which the binding energy is greater than the other light elements.

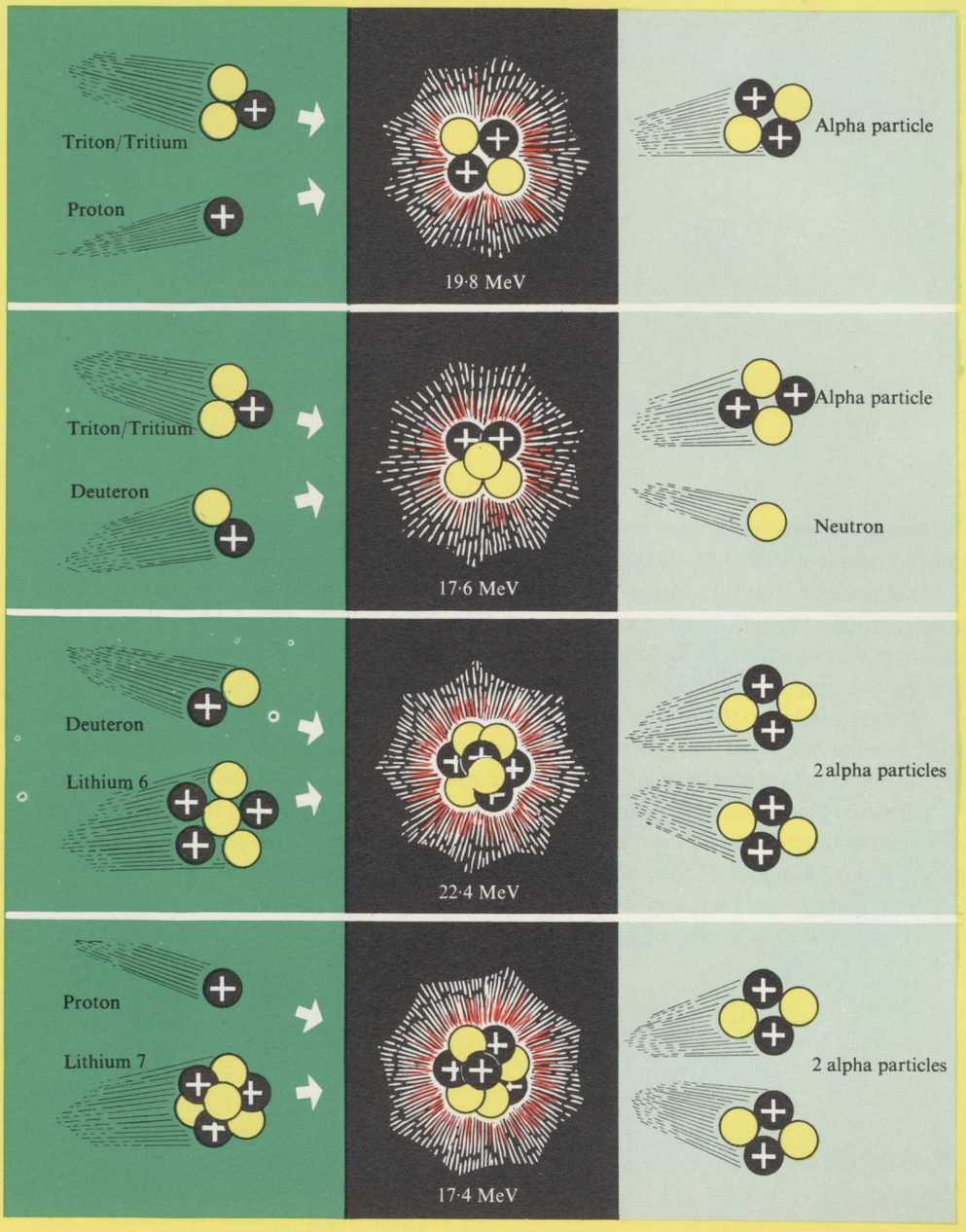


Diagram of the thermonuclear reactions of fusion in some atomic nuclei, and indication of the different energies released in them (expressed in MeV). In addition, there are numerous other thermonuclear reactions in which the fusion of light atomic nuclei with heavier nuclei occurs, with relative liberation of energy.

Phases in the process of fusion of atomic nuclei

ENERGY OF THE STARS

The energy of the stars or sun, a star itself, is the result of fission reactions of lightweight nuclei which occur at temperatures of 15–30,000,000° C.

It is thought that this energy is released in the carbon cycle and in the proton-proton chain. The relative probability of the carbon cycle and proton-proton chain depends on the temperature and the amount of carbon available. At low temperatures the proton-proton chain predominates, while the carbon cycle gains in importance with increasing temperatures.

In stars similar to the sun with internal temperatures in the region of 20,000,000° C, the two cycles are of more or less equal importance. In the hotter stars, probably all the energy derives from the carbon cycle, while the main source of energy in colder stars is the proton-proton chain.

According to the latest hypotheses, the carbon cycle exists in the fact that the nuclei of the hydrogen atom (protons) give rise to fusion with the production of nuclei of helium, releasing a certain quantity of energy, while the nuclei of the carbon atom function as catalysts in these processes. During the intermediate phases a whole series of transformation processes take place.

The cycle may be explained as follows:

$$C_6^{12} + H_1^1 = N_7^{13} + \text{gamma}$$

$$N_7^{13} = C_6^{13} + \text{beta (positron)}$$

$$C_6^{13} + H_1^1 = N_7^{14} + \text{gamma}$$

$$N_7^{14} + H_1^1 = O_8^{15} + \text{gamma}$$

$$O_8^{15} = N_7^{15} + \text{beta (positron)}$$

$$N_7^{15} + H_1^1 = C_6^{12} + He_2^4 + \text{gamma}$$

The proton-proton chain (in which the nuclei of hydrogen fuse amongst themselves, forming nuclei of new atoms of helium) also releases an enormous energy.

The cycle is as follows:

$$H_1^1 + H_1^1 = H_1^2 + \text{beta (positron)}$$

$$H_1^2 + H_1^1 = He_2^3 + \text{gamma}$$

$$^3He_2 + {}^3He_2 = 2\,{}^1H_1$$

Theories based on these types of reactions have a reasonable degree of success; however, it is possible that other nuclear processes, as yet unknown to us, do occur.

It is thought that the sun, a natural thermonuclear reactor, loses 4,000,000 tons of its mass every second. In this case, it could continue to release energy for another 30,000,000,000 years.

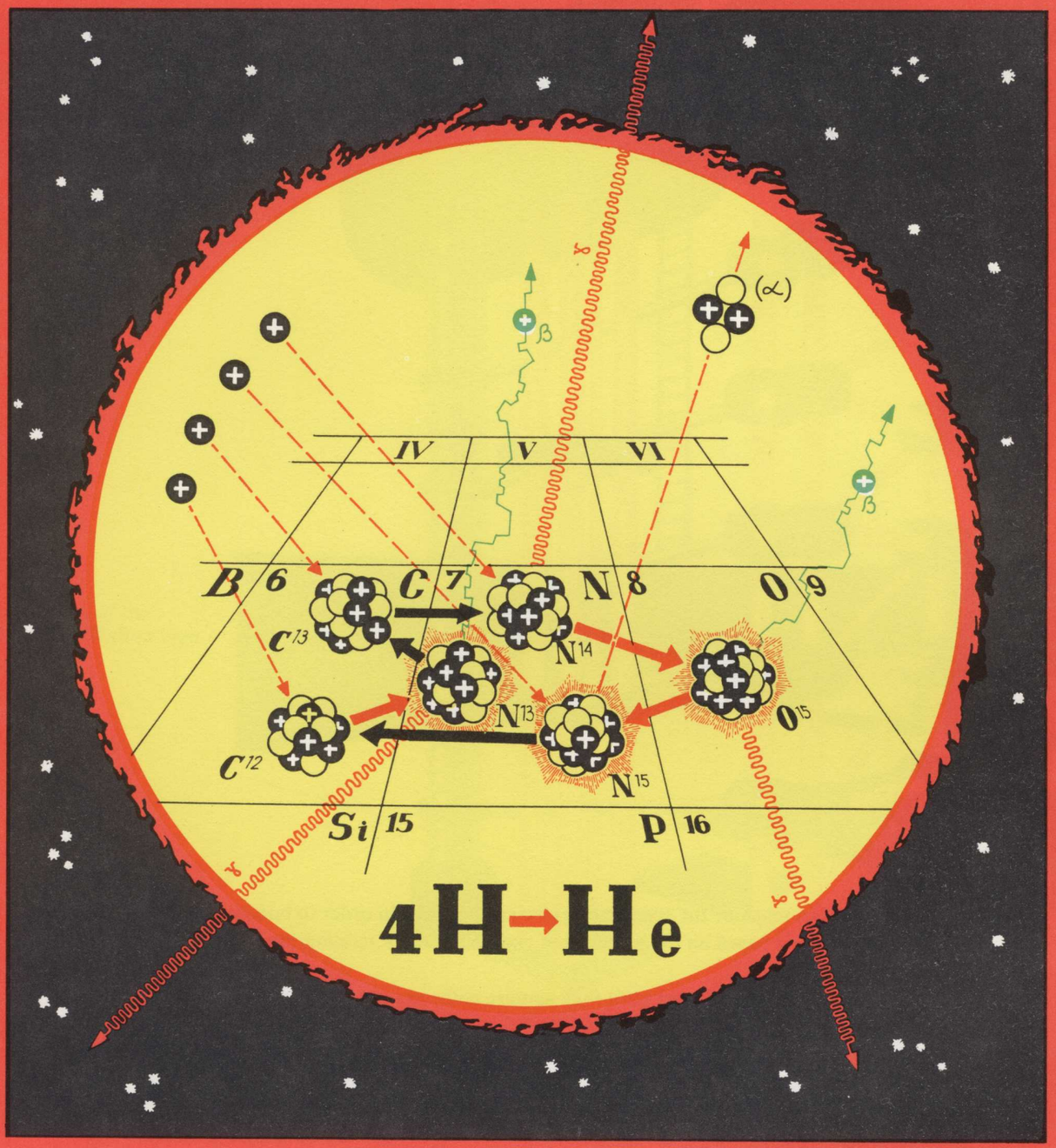


Diagram of thermonuclear reaction in stars

Inside stars, where temperatures reach 20,000,000° C, nuclear reactions develop between hydrogen (proton), carbon, nitrogen and oxygen. In the processes of this closed cycle, an atom of helium is formed from four atoms of hydrogen, releasing a vast quantity of energy which is part of that radiated by the star. The diagram illustrates the cycle of these reactions and the changes in the elements of the periodic system concerned.

ACCELERATORS

An accelerator is a machine for accelerating charged particles in order to bombard atomic nuclei. Every type of accelerator is based on the principle of charged particle acceleration in an electric and magnetic field.

The particles are accelerated until they acquire sufficient energy to disrupt the forces maintaining the stability of the nuclei.

Early nuclear science used fast particles emitted by natural radioactive substances to bombard the nuclei, but their energy was too low for a thorough exploration of nuclear structures. Nowadays a large number of accelerators have been built for this purpose – betatron, cyclotron, Cockcroft–Walton generator, linear accelerator, synchrocyclotron, synchrotron and Van de Graaff generator.

The electrostatic generator of Van de Graaff, built for the first time in 1931, consists of a large, hollow metal sphere and a continuous belt revolving around two pulleys, one of which is placed inside the sphere itself.

The sphere rests on an insulating support and is connected to the upper pulley by a conductor. An electric motor turns the lower pulley at high speed, moving the belt of silk or rubber.

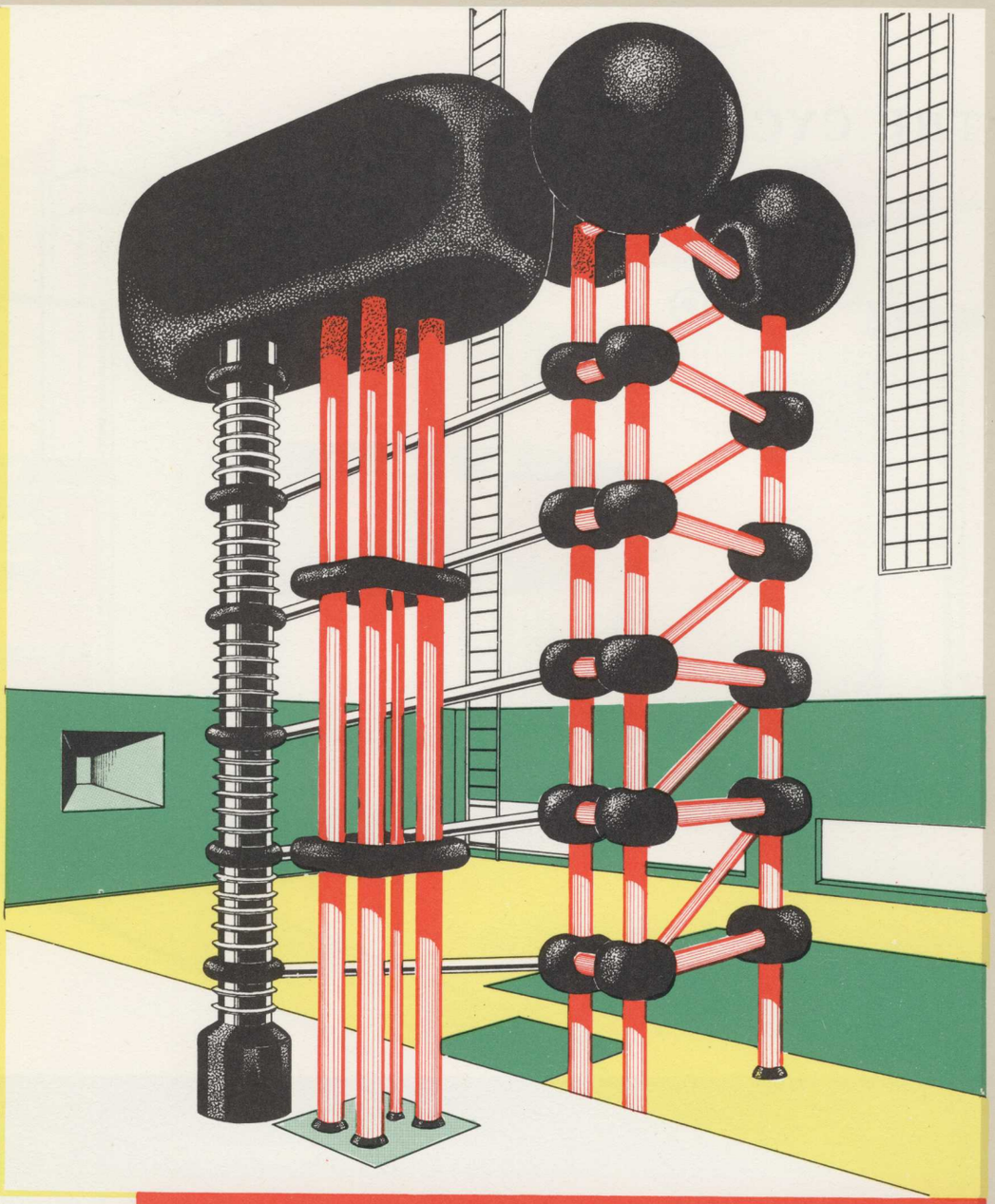
A high tension battery (tens of thousands of volts), is connected to the end of a brush close to the lower part of the belt. Running near this brush, the belt picks up its negative electric charge and transmits it to the sphere by means of the conductor joining it to the upper pulley. Consequently all the electric charge is distributed over the sphere's surface, while the belt discharges.

This process is repeated until the sphere reaches a potential of several millions of volts; then electric fields form inside an insulated vacuum tube inside the apparatus, accelerating the electrons or other charged particles entering it.

Accelerators are used for basic nuclear research in physics, with therapeutic scopes in medicine and also for obtaining radioactive isotopes.

Accelerators are also used in research on the structure of atomic nuclei to discover the properties of their components and their forces of interaction.

Accelerator of the Cockcroft–Walton type



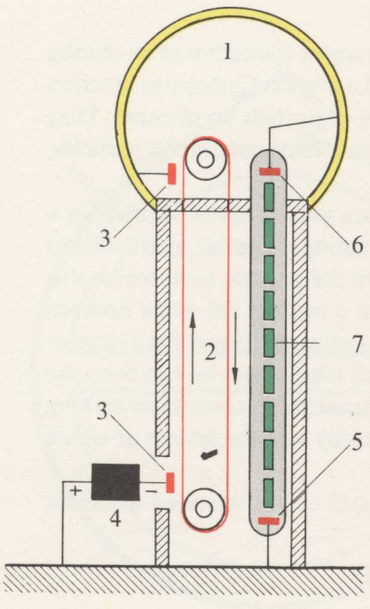


Diagram of the Van de Graaff electrostatic generator

1 Hollow metal sphere.
2 Continuous belt, driven by a motor and revolving around two pulleys or rollers.
3 Brush for transmitting the charge from the source to the belt, and from belt to conductor.
4 High tension battery (tens of thousands of volts).
5 Target.
6 Source of ions.
7 Accelerator vacuum tube.

THE CYCLOTRON

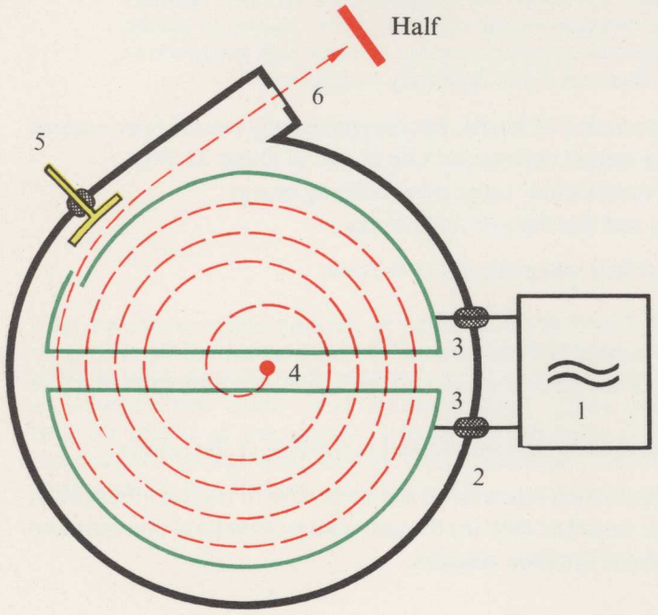
In the cyclotron, charged particles are accelerated along a spiral trajectory under the action of an electric or magnetic field. The first cyclotron of this type was built in 1931 by E. O. Lawrence. Cyclotrons function at an energy of several MeV on average. The energy depends on the type of particle accelerated. They are used in nuclear research for the acceleration of atomic particles: protons, deuterons, alpha particles, etc.

They work in the following way: two halves of a cylindrical box are placed under vacuum in a magnetic field. Between these two halves, there is an electric field of alternating potential, synchronized with the movement of the ions. The source of ions is at the centre. When the particle (ion) leaves this source, it moves along the circumference of the magnetic field, and when it reaches the space between the semicircular electrodes it is accelerated by the electrical field. Thus the radius of the particle's circular trajectory is greater at the entry to a semicircular electrode than that which it possesses on exit from the other electrode; the particle therefore assumes a spiral movement. Synchronization consists in making the maximum value of the electric accelerator field coincidence (synchronize) with the instant at which the particle crosses the area between the two semicircular electrodes.

In following this spiral, the particle accelerates more and more, until it has acquired sufficient energy on exit to bombard the target.

Cyclotrons are very complex machines and some are very large in size.

General appearance of a cyclotron



Working diagram

1 High frequency generator.
2 Vacuum chamber circular in shape (placed between electromagnet).
3 Semicircular electrodes.
4 Source of ions.
5 Electrode for the deviation and extraction of particle streams.
6 Aperture for the exit of streams.

NUCLEAR REACTOR

The nuclear reactor is a machine in which controlled chain reaction fission takes place. In the fission of a nucleus of combustible nuclear fuel (uranium, plutonium, etc.), new free neutrons are created, which cause fission in new nuclei, thus developing a chain process.

A reactor has three main fields of application:
(1) production of energy;
(2) production of nuclear fuels and explosives (uranium 233, plutonium 239);
(3) experimental work in physics, chemistry, biology, nuclear techniques and production of radioactive isotopes.

Reactors may be classified according to their power:

low power (100–1,000 kW)
medium power (1,000–10,000 kW)
high power (over 10,000 kW).

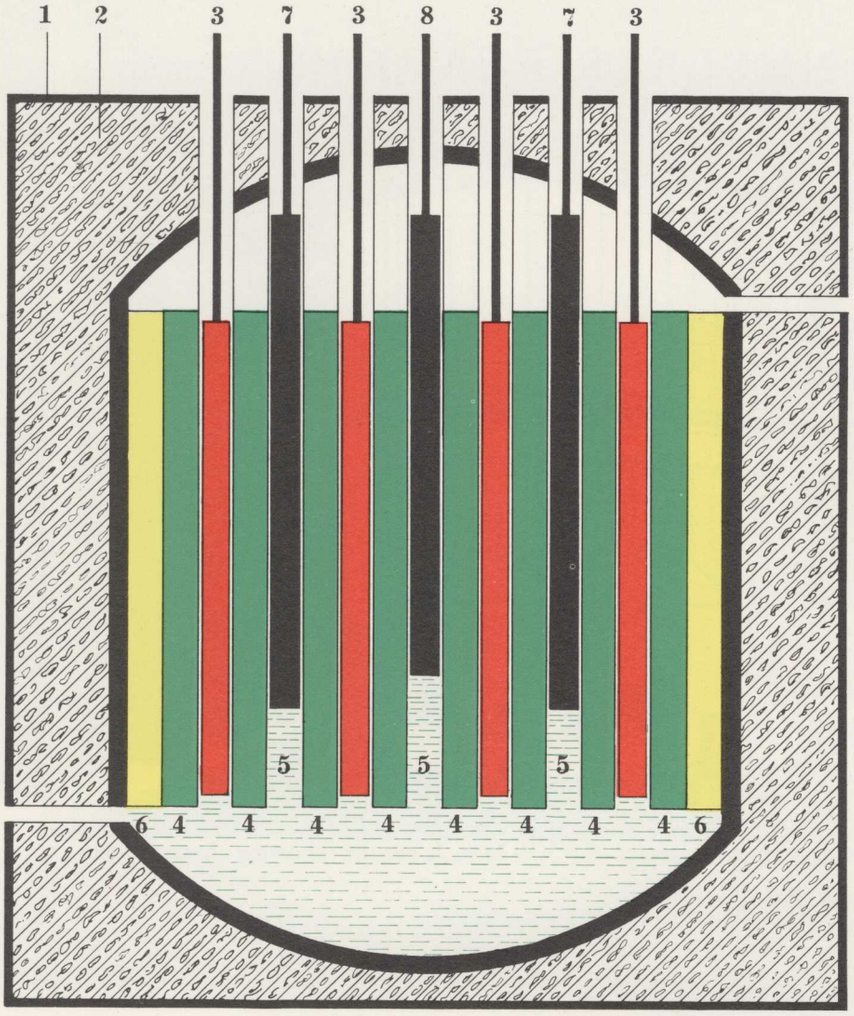
To exploit the energy released in fission there are three necessary conditions:

(a) simultaneous fission of an enormous number of nuclei, because the energy released per nucleus is almost insignificant (10^{12} fissions a second correspond to a power of about 32 W);
(b) process of chain fission, so that the 'combustion' keeps on producing energy;
(c) possibility of regulating the intensity and duration of the process.

The structure of a nuclear reactor is described schematically as follows:

a 'heart or core' where chain reaction of fission develops;
a cooling system, which absorbs and dissipates the heat created in the 'core';
biological protection (screening all parts of the reactor which emit radiations) to insure the safety of personnel working near by;
a regulating system with control instruments, for the running and utilization of the reactor.

The non-powered reactor is used for experimental research on the behaviour of reactors themselves under different working conditions or systems, to collect data for the calculation, structural planning and choice of work system in heavy water and natural uranium reactors.



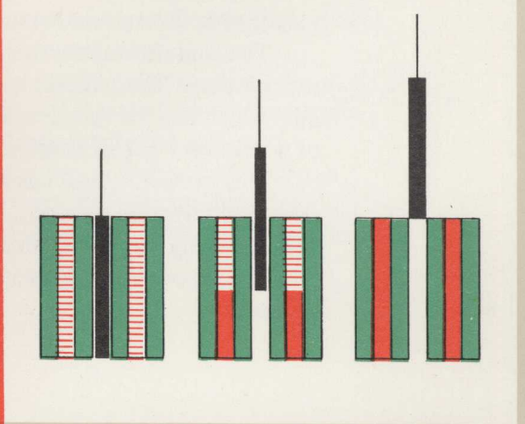
Basic parts of a nuclear reactor

1 Container of the reactor
2 Biological protective shield (usually concrete)
3 Nuclear fuel (U 235, U 233, Pu 239)
4 Moderator (heavy water, beryllium and graphite)
5 Cooling system (very often common water)
6 Neutron reflector (beryllium, graphite)
7 Control rods (cadmium, boron and others)
8 Safety rods (neutron absorber)

Diagram of the structure of a nuclear reactor

Nuclear reactors are machines for controlled fission reaction of heavy atomic nuclei with the release of energy. Every nuclear reactor consists of a container in which are situated the nuclear combustible fuel and the other constituent elements of the reactor itself.

The regulation of the number of secondary neutrons, that is, the regulation of the fission process in the nuclear reactor, occurs in different ways. For this purpose metal control rods, potent absorbers of neutrons, are mainly used. By lowering or raising the control rods the power of the reactor, that is, the intensity of the chain reaction, can be regulated, and the temperature and heat developed by the reactor can therefore be controlled.



EXPERIMENTAL NUCLEAR REACTOR

The illustration shows an experimental reactor of 6·5/10 MW. It has the following characteristics:

Type: heterogeneous heavy water reactor
Nominal power: 6·5 MW
Maximum power: 10 MW
Average neutron flow: $2{\cdot}9 \times 10^{13}$ neutrons/cm^2 sec.
Nuclear combustible fuel: enriched uranium with 2 per cent uranium 235
Moderator: heavy water
Reflector: graphite
Cooling system: forced circulation of heavy water

Purpose: use of radiations for research on the structure of matter, and the influence of radiations on physical, chemical and biological characteristics of materials; production of isotopes; research on fuel elements for new reactors; study and analysis of reactors in operation for the collection of experimental scientific data; formation of specialized control panels for protection from radioactive contamination.

Structurally this reactor is an aluminium container filled with heavy water, in which the uranium bars or rods are placed in uniform order. To obtain a chain reaction, a certain mass (called critical) of uranium and heavy water is necessary. During fission, heat is released as well as intense neutron radiation and other types of radiation.

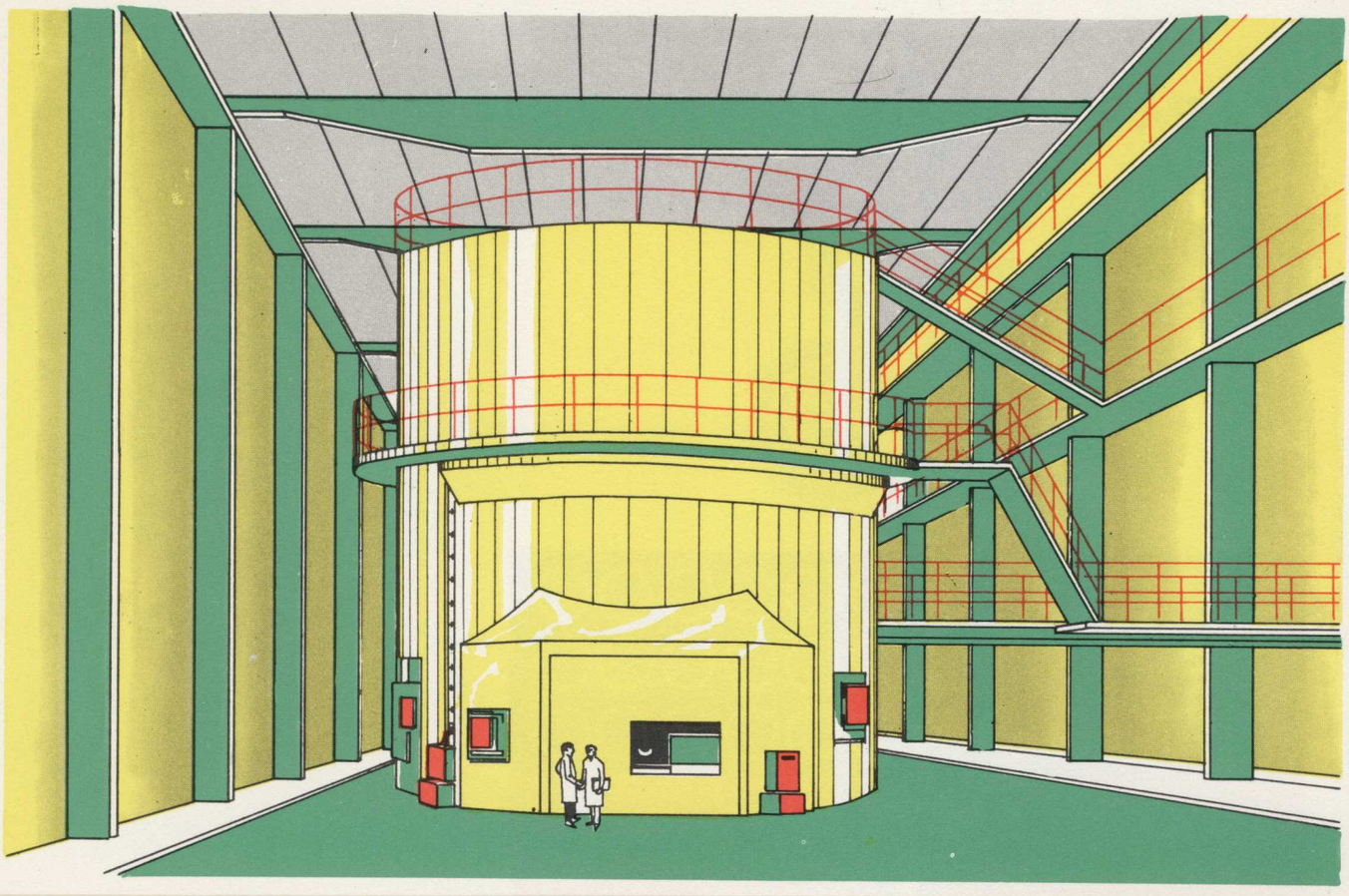
The heat from the energy reactors is exploited for practical purposes, while in experimental ones the radiations are utilized for study and research.

Radiations are made use of in two ways: by introducing various chemical elements into the reactor and subjecting them to the radiations, or by moderating the stream of radiations externally, producing reactions in the nuclei towards which the streams are directed as a target.

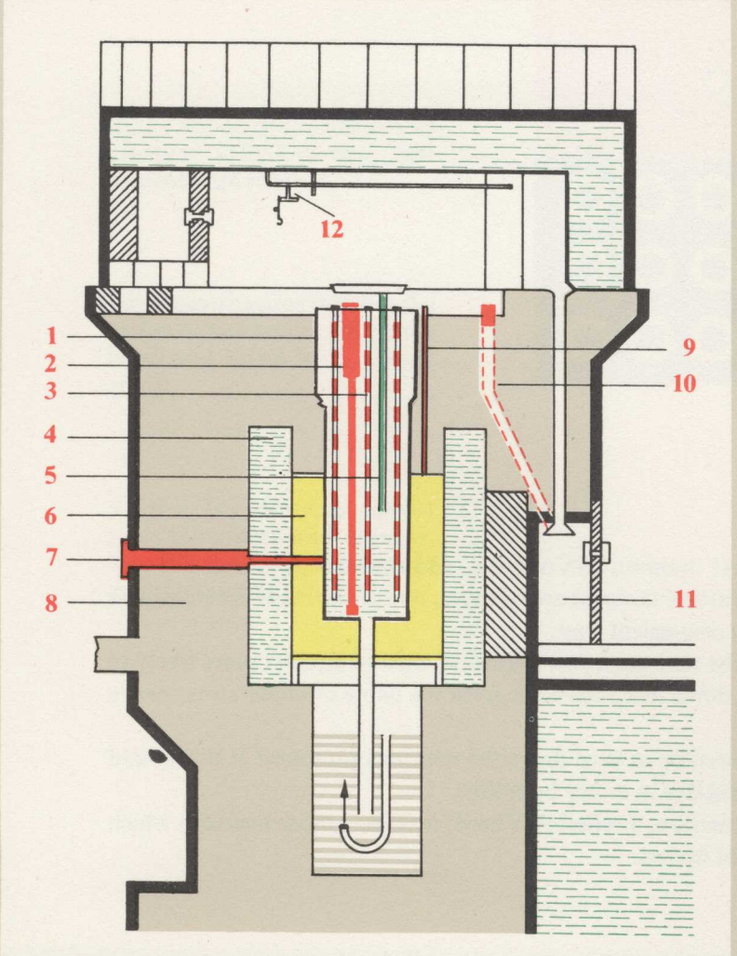
The container of the reactor is lined with material which reflects the neutrons, keeping them within the container. The reflector is made of graphite, 0·6 m thick. This lining is in turn covered with a thicker one, which has the function of protecting personnel from radiations; it consists of a covering of 0·5 m of water and 2·5 m of concrete.

This protective wall has apertures for introducing the samples to be irradiated, or from which the stream of radiation may exit. These apertures are called experimental channels or ducts. The reactor we are describing has seven horizontal ducts and forty-five vertical ones.

The experimental capacities of the reactor are considerable and several hundred experts may work on them.



An experimental reactor of 6·5/10 MW



Vertical section through a reactor

1 Steel container
2 Fuel elements (uranium bars/rods)
3 Vertical channels/ducts for irradiation of isotopes
4 Protection (water)
5 Control rods/bars
6 Graphite reflector of neutrons
7 Horizontal experimental channel/duct
8 Concrete screen
9 Vertical channel/duct in the graphite reflector for irradiation of materials
10 Transport tube for isotopes
11 Reception chamber for introducing isotopes into the containers
12 Crane or davit for manipulating isotopes

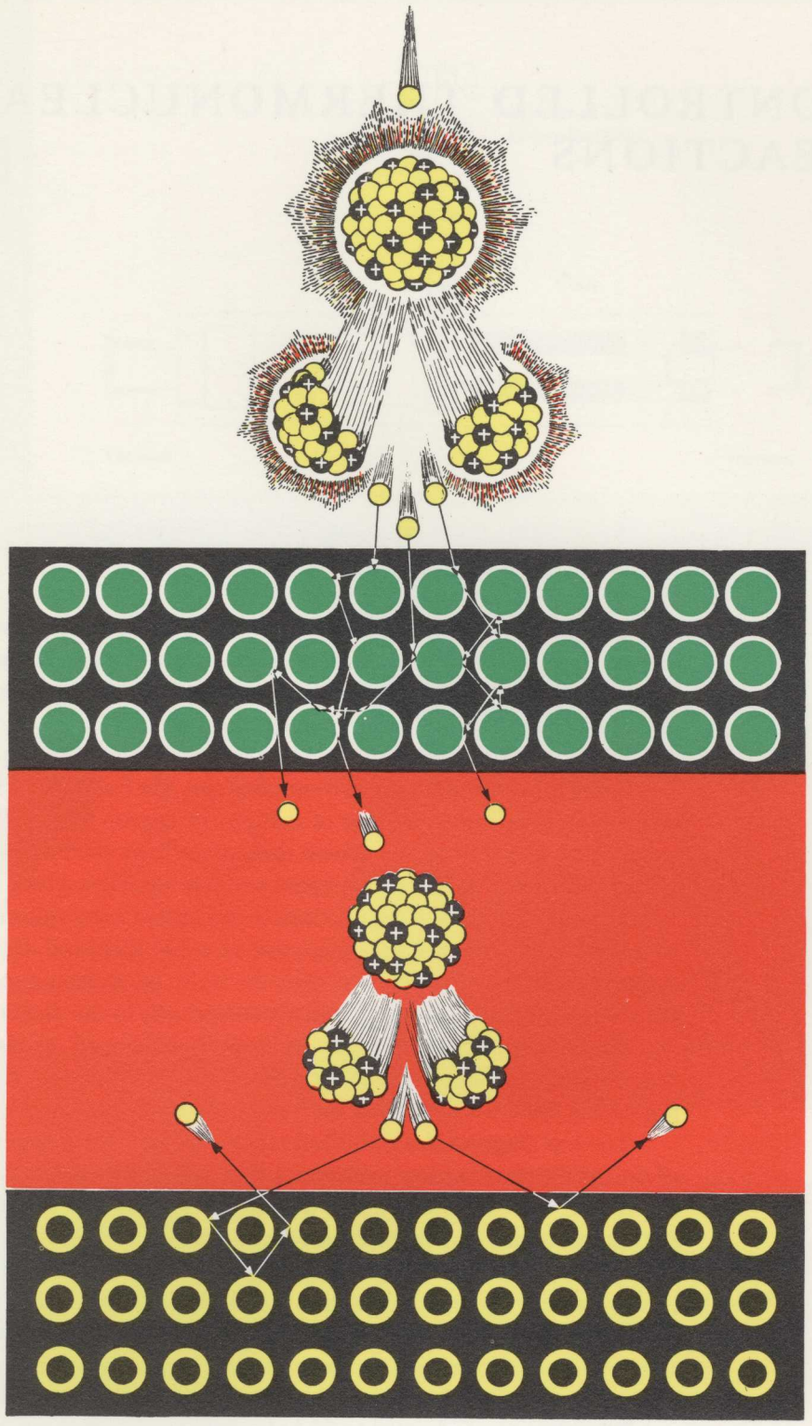
NUCLEAR FISSION IN THE REACTOR

Once it had been experimentally verified that uranium 235 is fissile, and that during fission 2–3 new neutrons per nucleus (capable of producing further fissions) are released, one of the main problems was to discover how to produce these fissions in a convenient way.

In fact, it was necessary to slow down the new neutrons, because a slow neutron is more likely to cause fission. Substances capable of slowing down neutrons were given the name of moderators; heavy water is one of the best moderators.

The use of the moderator has made it possible to slow down the neutrons produced in fission and thus to provoke a chain reaction, which takes place in a very brief time.

For maximum limitation of neutron dispersion, a reflector is used; it reflects those neutrons which leave the fissile mass without having produced fission.



In the fission of the nucleus of uranium 235, 2–3 new, fast neutrons are released.

For these neutrons to cause the fission of new nuclei, they must be slowed down with a moderator.

So that the neutrons cannot leave the system and disperse, the reflector is used to replace them in the fissile mass.

Diagram of the fission of uranium nuclei in a nuclear reactor

CONTROLLED THERMONUCLEAR REACTIONS

In many laboratories, attempts are now being made to carry out thermonuclear reactions in specially designed apparatus; at present these occur only in stars and thermonuclear weapons.

Several types of apparatus are currently used: they may be distinguished by the way the reaction is contained and the methods of heating the plasma.

Normally the plasma is formed by means of high-power electrical discharges through a cylinder. The cylinder has strong walls and contains gas, like hydrogen, for example, at a given pressure. Because of the high temperature of tens of millions of degrees, the collisions between the atoms of gas are so violent that all the electrons detach themselves from the nucleus. Under such conditions the atoms no longer exist; there are only bare nuclei and free electrons which move separately.

The basic problem is how to isolate the heated mass (plasma) from the walls of the apparatus, for all known materials melt and evaporate at a few thousand degrees. For insulation, externally created magnetic fields may be used to protect the walls, or, at least in part, the strong internal fields created by the plasma itself in motion (as shown schematically in the diagrams).

The magnetic field represents an impenetrable 'wall' to the plasma, that is, a sham wall which is nevertheless capable of maintaining the particles within the plasma as a result of its action, and thus preventing them from reaching the 'real' walls of the container.

The top diagram is a simplified scheme of the 'Ogra' apparatus built in the USSR. The diameter of the cylindrical chamber measures 1·4 m, while the length of the operative part of the chamber may measure 12 m. The coils produce a magnetic field, which has a value of 5,000 gauss at the centre and 8,000 gauss around the edges. Inside the chamber is a pressurized vacuum: the residual gas has a pressure of less than one thousand millionth of atmospheric pressure. The energy consumed by the apparatus is enormous; one coil alone consumes 4,000 kWh of electric energy.

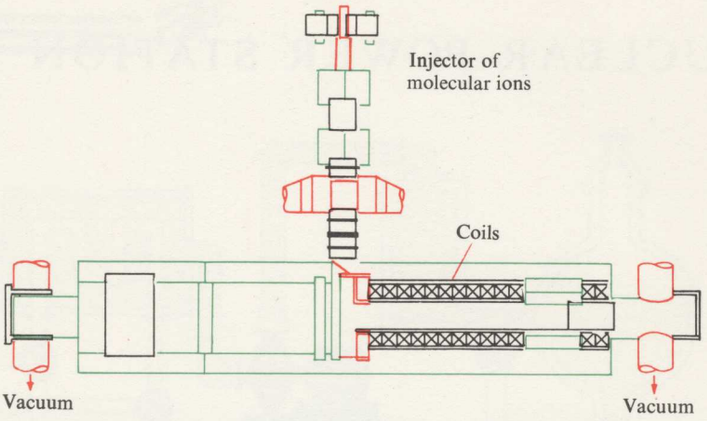
The plasma is heated by injecting it with molecular ions of heavy hydrogen (hydrogen molecules have two atoms: removing an electron from them, one obtains a molecular ion). For the introduction of these ions, a special apparatus has been built which is like a small accelerator.

The ions are accelerated to 20 keV, and then injected into the chamber vertically in relation to its axis. The ions move along a spiral inside the chamber. In collision with other particles, the molecular ion may split into two deuterons. The deuterons continue the spiral motion, transmitting energy in the collisions; the process of fusion may also occur. In this way the deuterons may traverse up to 100,000 km.

The central diagram shows the Russian 'Alpha' and English 'Zeta' types of apparatus. In the 'Zeta' apparatus the vacuum is created in the ring-shaped chamber, which has an internal radius of 1 m, while the average radius is 1·6 m. The chamber is of aluminium.

Inside the main chamber is the complementary chamber, composed of 48 metallic tubes insulated from each other. Its function is multiple: it ensures electrical stability by eliminating various short circuits, absorbs the heat from the heated gas, thus cooling the tubes, etc. The chamber is filled with low pressure deuterium (about 10^{-4} Hg).

Thus the thermonuclear reactor, compared with nuclear reactors, offers very many advantages. It functions without producing radioactive isotopes; it uses small quantities of fuel, thus presenting less potential danger; it offers the possibility of obtaining electrical energy directly from the motion of the charged products of fusion; above all, it is economical because of the ready availability of the fuel.



Simplified diagram of the 'Ogra' type reactor

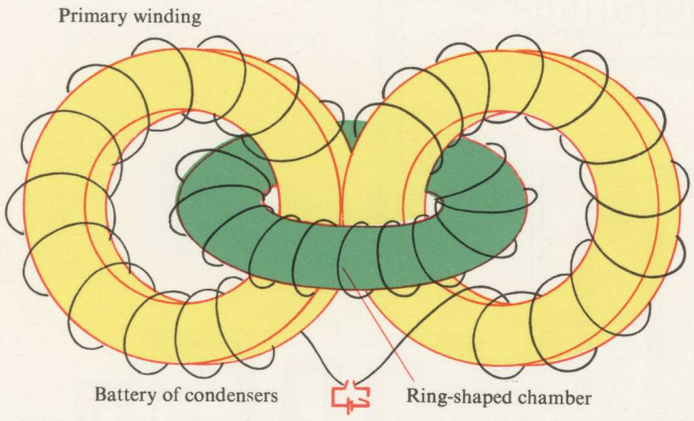
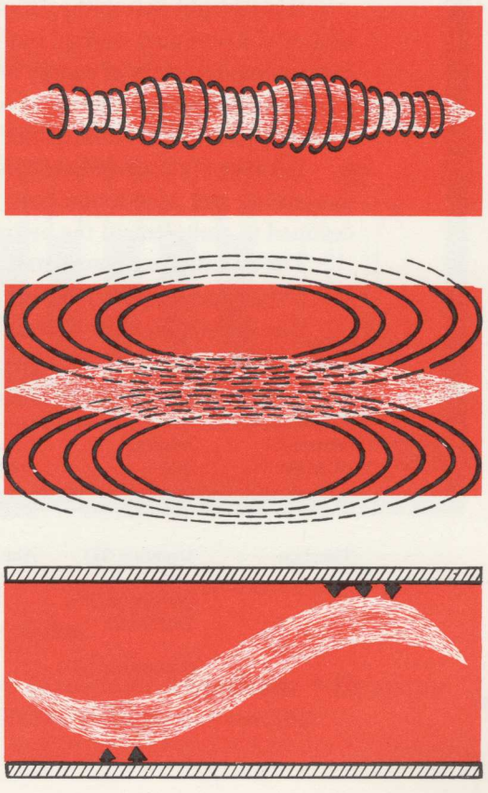


Diagram of the 'Alpha' (Russian) and 'Zeta' (English) types of reactor



The magnetic fields are capable of insulating the plasma from the walls of the cylinder. *Top:* magnetic field created as a result of the process in the plasma itself; *centre:* complementary magnetic field created externally by means of an intense electric current; *bottom:* action of the cylinder's metal walls which repel the plasma.

NUCLEAR POWER STATION

A nuclear power station is a collection of machinery for the production of electrical energy, in other words, a power station utilizing nuclear energy.

Roughly speaking the nuclear power station is composed of the nuclear reactor which acts as an 'oven', the steam generator or 'steam boiler', and the steam or gas turbines connected to the generators of electric energy (dynamos).

It is thought that in the future the cost of nuclear energy will gradually decrease compared with the cost of conventional energy, but at present the tendency is to build nuclear power stations only where conventional sources of energy are lacking.

It is evident that reserves of conventional fuels are not inexhaustible, and already this fact constitutes a serious problem in some countries.

Because of the enormous concentration of energy in nuclear fuel, because the prospects of a decrease in working and production costs, and because they can be built anywhere, nuclear power stations are destined to complement the hydro-electric and thermic power stations.

The first nuclear power station was opened in the Soviet Union on 27 June 1954. Its power is 5,000 kW. Other nuclear power stations have also been built or are under construction in various countries.

The development of nuclear technology has required the adoption of new materials among which are listed the following:

Material of origin	Nuclear fuel	Construction materials	Moderator of neutrons	Heat exchanger	Regulators	Biological protection
Uranium	Uranium 235	Steel	Water	Water	Boron	Concrete
Thorium	Uranium 233	Aluminium	Heavy water	Helium	Cadmium	Water
	Plutonium 239, Zirconium		Graphite	Carbon dioxide	Hafnium	Lead
	(Plutonium 241)		Beryllium oxide	Melted metals (sodium, potassium, lithium and others)		Iron (also hafnium, boron)

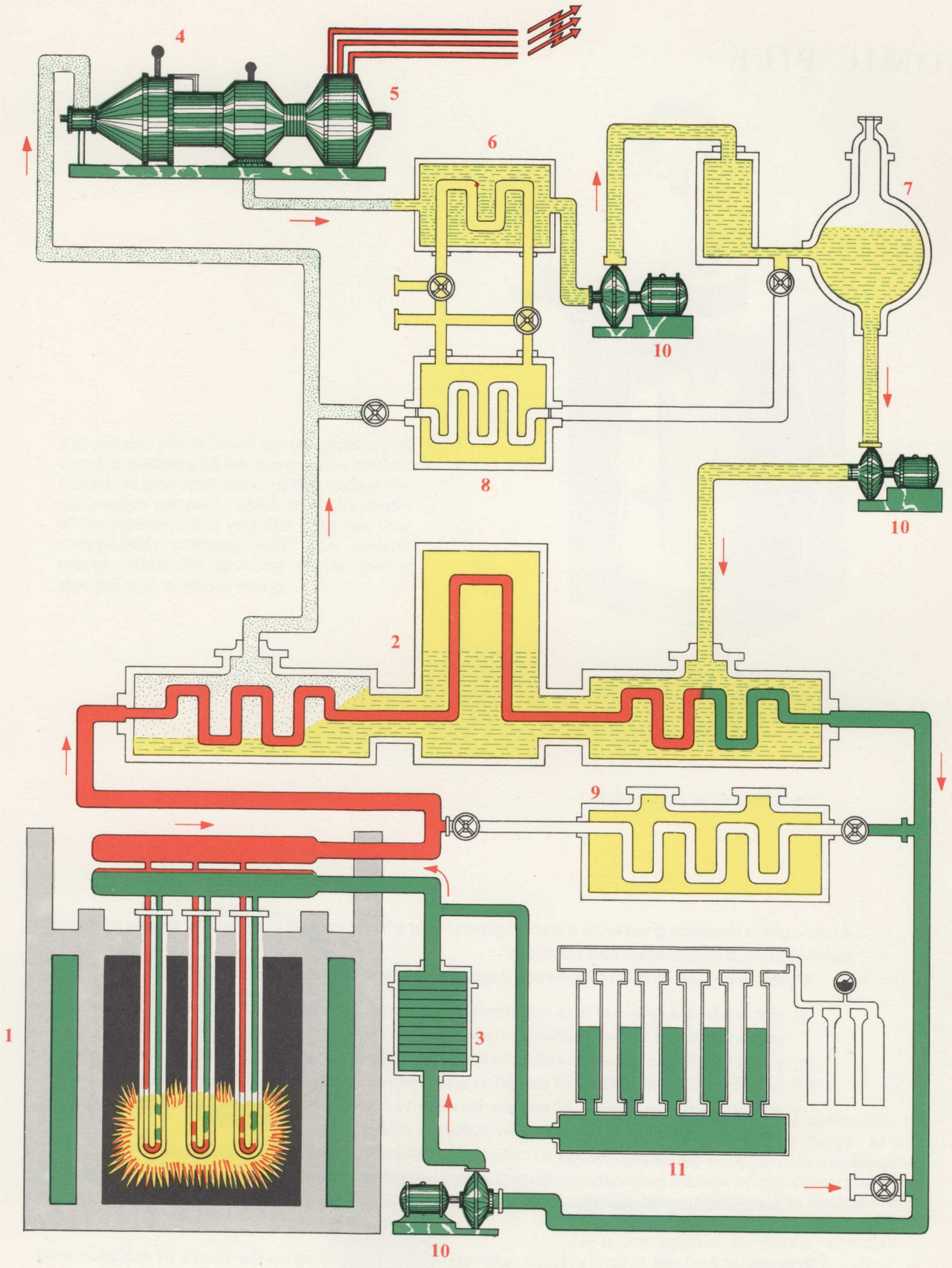


Diagram of a nuclear power station

1 Nuclear reactor **2** Heat exchanger **3** Filter **4** Steam turbine **5** Generator **6** Condenser **7** De-aerator (demineralizer) **8** Starter condenser **9** Reserve condenser **10** Pump **11** Expansion chamber

ATOMIC PILE

Atomic pile is the name given to an electrical generator in which the energy released by atomic radioactive disintegration is transformed into electricity.

Atomic piles may be one of five types, depending on how the energy is transformed:

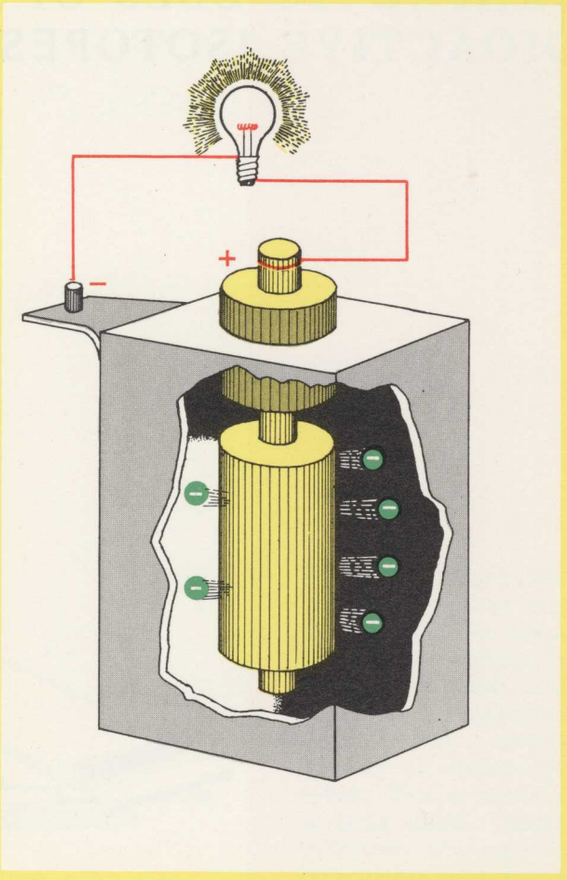
(a) pile in which a source of beta radiations is placed inside a hollow metal sphere to create a difference of potential between sphere and source
(b) pile in which the radioactive radiation ionizes the atoms of gas, and the ions thus formed generate an electric current because of the difference of contact potential in the electrodes
(c) pile in which the surface of contact between two semi-conductors of for example type p-n, becomes the source of current under radiation action
(d) pile in which the heat energy of radiation is utilized for heating thermoelements
(e) pile in which a luminous substance is placed under beta radiation; as a consequence of the alpha particle action in this phosphores, scintillations occur which are transformed through photo-elements into electricity.

These piles are used to feed various radio apparatus. Depending on the source of radiation used, the piles can last twenty to thirty years or more.

The diagram shows the mechanism of a pile.

The direct conversion of nuclear energy into electric energy – that is, without passing through the baser form of energy (heat) and without traditional rotation systems, (turbines – generators) – is one of the main problems of modern technology.

The atomic pile is based on the principle of direct conversion of the energy from nuclear radiations into electricity. In this variant the radioactive material, which is at the centre of the capsule, emits very fast electrons, thus continuously charging itself with positive energy, while the covering of the pile is charged with negative energy.



Appearance of an atomic pile

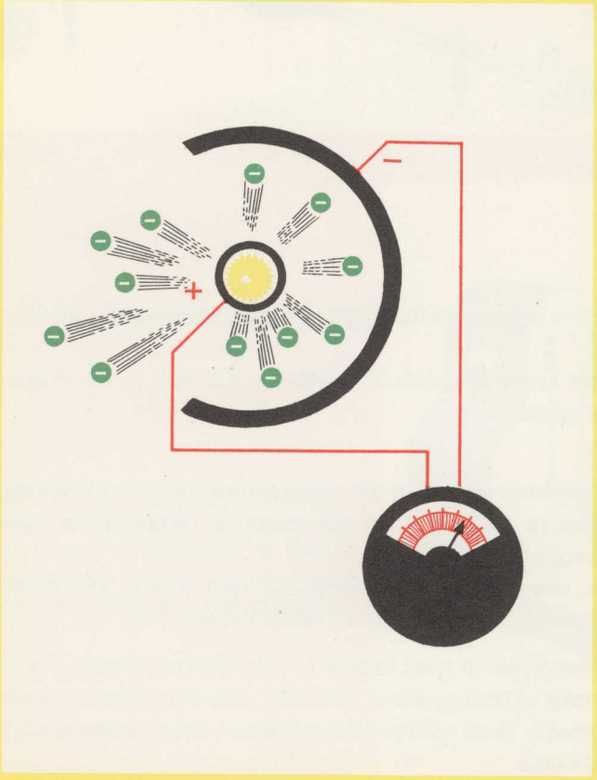


Diagram of the working of a pile

The simplest example of the conversion of nuclear energy to electrical energy: at the centre of a metal hemisphere is a radioactive source – an emitter of particles carrying a negative charge, electrons. The electrons form the negative pole of this hemisphere. When this is connected to the source of radiation through a conductor, an electric current is obtained.

THERAPEUTIC USES OF RADIOACTIVE ISOTOPES

Modern medical science makes use of radioactive isotopes in the diagnosis and treatment of a number of diseases.

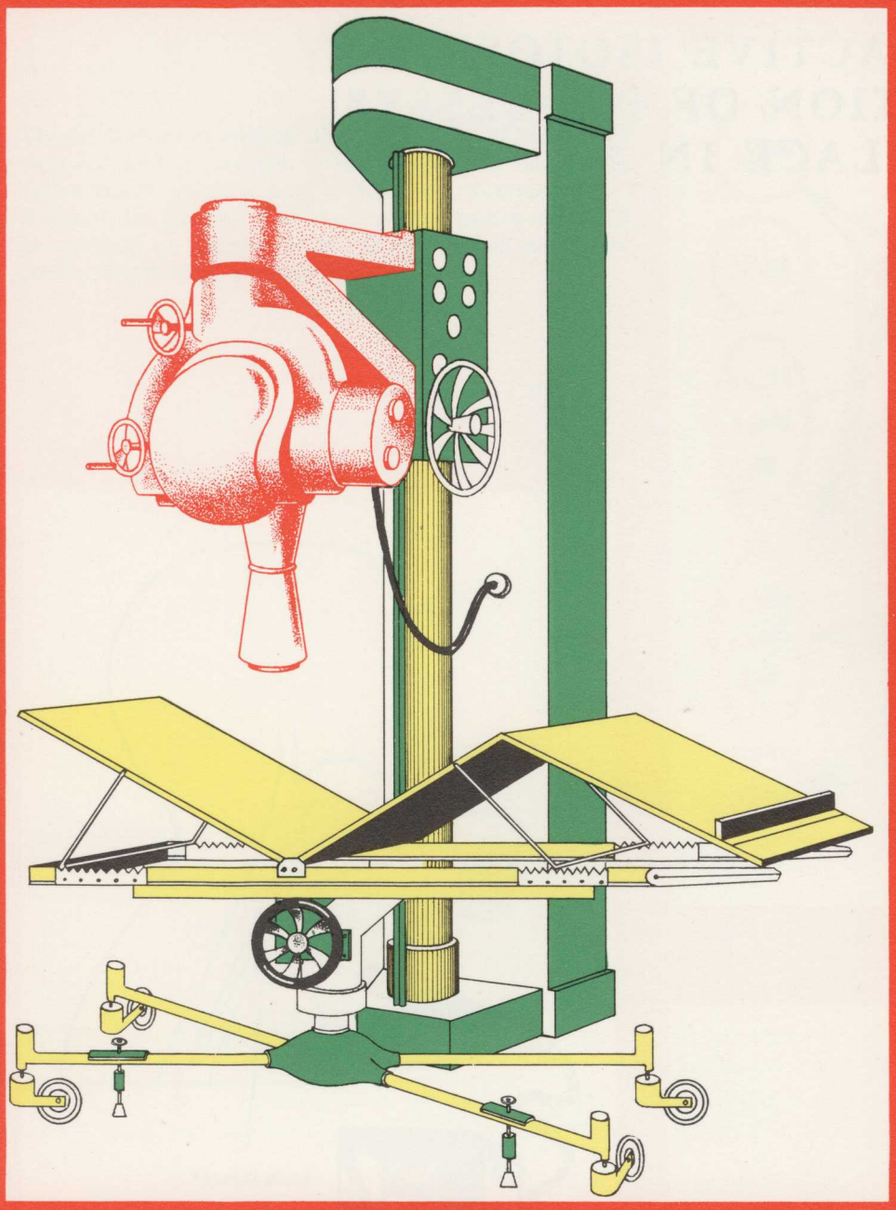
In many countries there are centres where artificial radioactive isotopes are used in the diagnosis and cure of particular illnesses, especially malignant tumours.

Radioactive isotopes are used as follows:

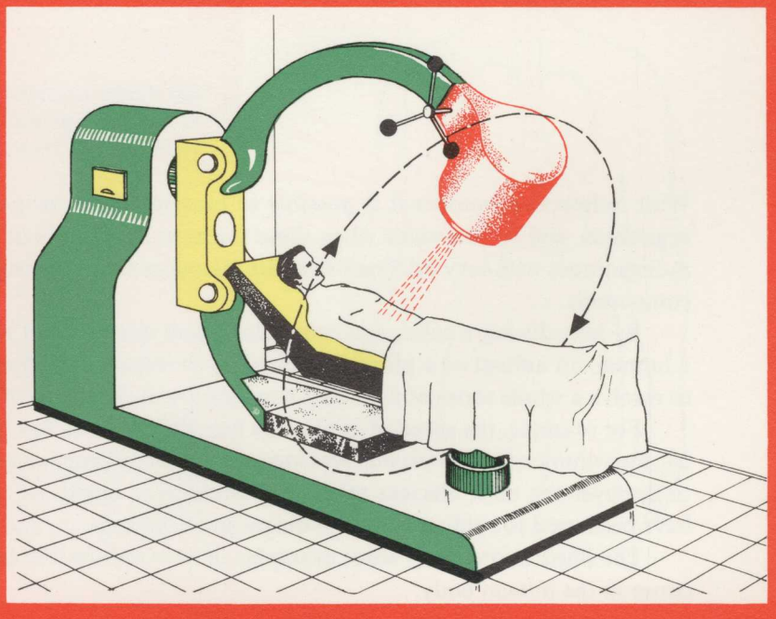
(a) in diseases of the thyroid glands and endemic goitre, in the measurement of blood volumes, in the analysis of the life of red corpuscles, in the location of cancer and its metastases in various organisms, in the study of the movement of thrombocytes

(b) in the therapy of Basedow's disease, cancer of the thyroid gland, skin, womb and bladder, carcinoma of the pleura, chronic leukaemia, and some eye and skin diseases, etc.

Some medical institutes employ radioactive cobalt to treat tumours in the internal organs. Gamma rays from the cobalt act mostly on the young cells of the organism. Since the cells of malignant tumours multiply rapidly, a stream of gamma rays directed at them with precision destroys them, doing much less harm to the healthy tissue than to the diseased tissue.



The cobalt source is used to irradiate tumours with gamma rays from radioactive cobalt. Beneath is the patient's couch, and above it the apparatus which contains a certain quantity of radioactive cobalt. This is inside a covering shield. During treatment, the gamma rays come out of a special aperture.



In order not to contaminate healthy organs unnecessarily, this type of cobalt source is constructed in such a way as to revolve around the patient stretched out in a horizontal position.

USE OF RADIOACTIVE ISOTOPES IN THE EXAMINATION OF PROCESSES WHICH TAKE PLACE IN AN ORGANISM

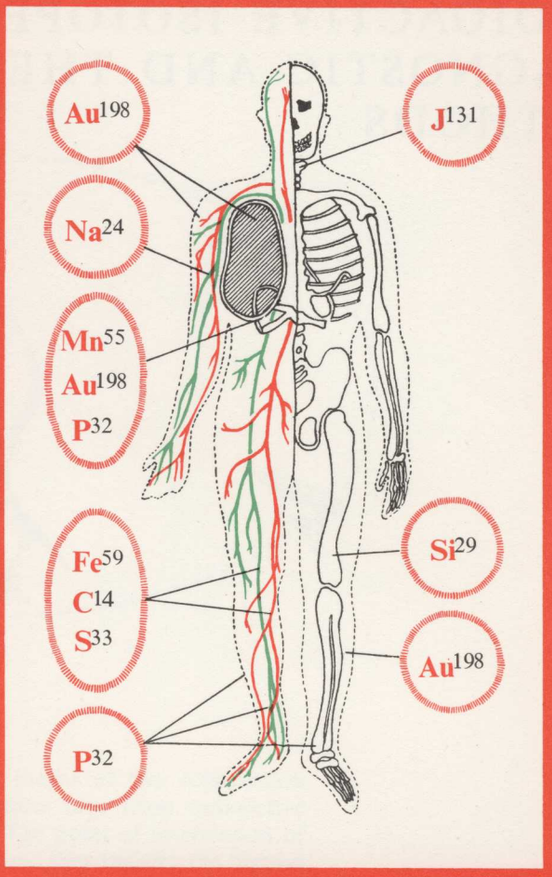
With radioactive isotopes it is possible to examine the principal processes which take place in living organisms, and to determine when these function incorrectly in illness. To do this, small quantities of radioisotopes with very brief half-lives are introduced into the organism in the form of suitable chemical compounds.

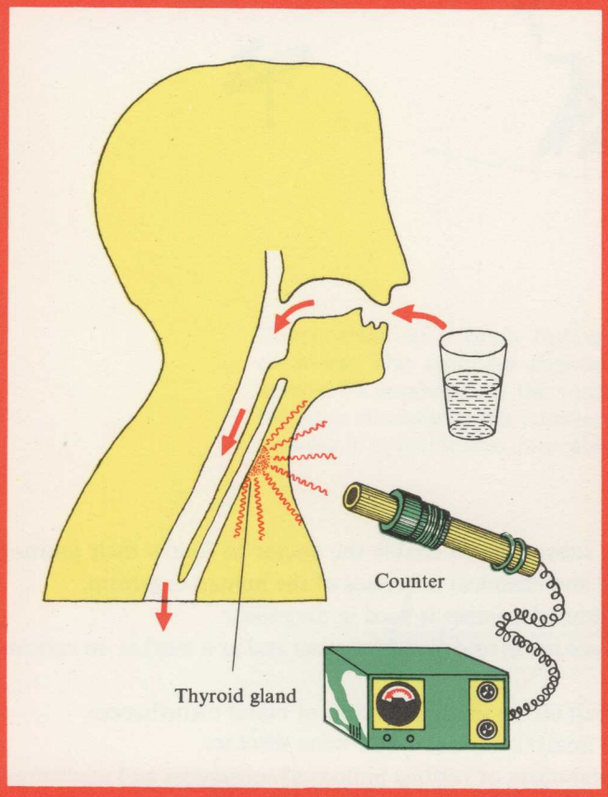
By introducing a substance containing small quantities of radioactive atoms into the organism of a human, an animal or a plant, it is possible to trace their diffusion, where they accumulate, and thus to resolve a whole series of problems connected with the study of biological processes.

For example, the speed of the human blood circulation has been measured with radioactive sodium 24; the volume of blood plasma was measured with radioactive iodine 131; radioactive iron 59 was used to discover the most efficient method of conserving blood for transfusion; other radioactive isotopes have been used to study methods of diagnosis in cancer.

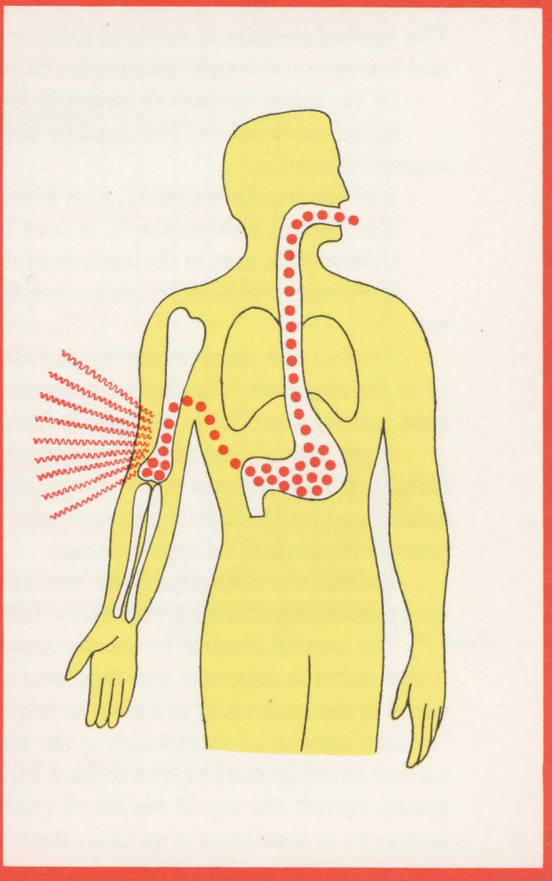
The illustrations show some examples of how radioactive isotopes are used in the analysis of processes in the human body.

The marked atom method, the substitution of an element with radioactive isotopes in substances with non-radioactive atoms which is used in diagnosis, treatment, etc., is based on the fact that various radioactive elements accumulate in definite parts of the human organism: bones, blood, liver, endocrine glands, etc.





By measuring the intensity of iodine radiation which the thyroid gland absorbs from the blood, one can determine both the quantity of iodine absorbed, and the quantity of hormones in the gland itself.



If foods contain marked atoms, the passage of certain substances can be traced through the organism, among others the accumulation of calcium and phosphorus in the bones.

Use of radioactive isotopes in the examination of processes which take place in an organism

RADIOACTIVE ISOTOPES IN DIAGNOSTIC AND THERAPEUTIC METHODS

The method consists in marking some organic substances to enable the doctor to follow their journey and destination through the complex biological and chemical processes of the human organism.

Of the many radioactive elements, only a limited number is used in diagnosis.

Radioactive iodine 131 is used for the analysis of thyroid gland function and as a marker on various organic substances.

Radioactive chromium 51, iron 59 and cobalt 60 are used in analysis of blood disturbances.

Radioactive phosphorus 32 is used in the analysis of blood and bone diseases.

Carbon 14 is used in the analysis of the metabolism of various biological substances and medicines.

Radioactive sodium 24, potassium 40 and chlorine 36 are employed in the analysis of metabolism, etc.

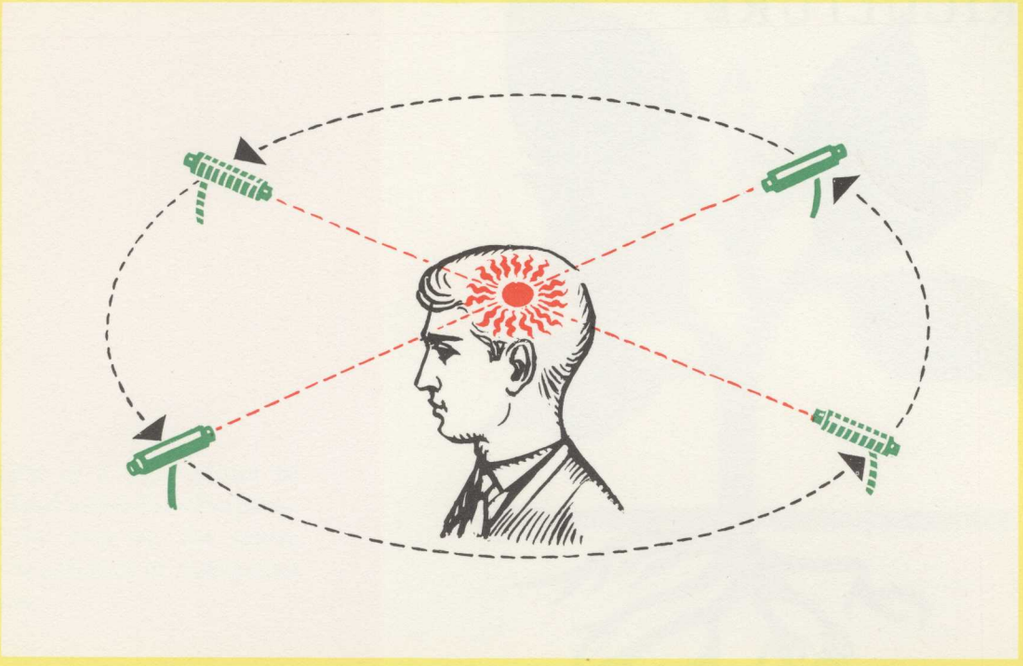
The fact that some radioactive isotopes accumulate in cancerous tissue of certain organs is made use of in the diagnosis of malignant tumours and their metastases. For example, radioactive arsenic 74 is used, among other things, to localize brain tumours.

In the annihilation of the positron emitted by the atomic nucleus of arsenic 74, two gamma rays are formed. If these gamma rays are registered by two aligned counters, it is possible to locate the tumour quickly and with precision, as it is situated at the point of intersection of the lines connecting the counters (see top illustration on opposite page).

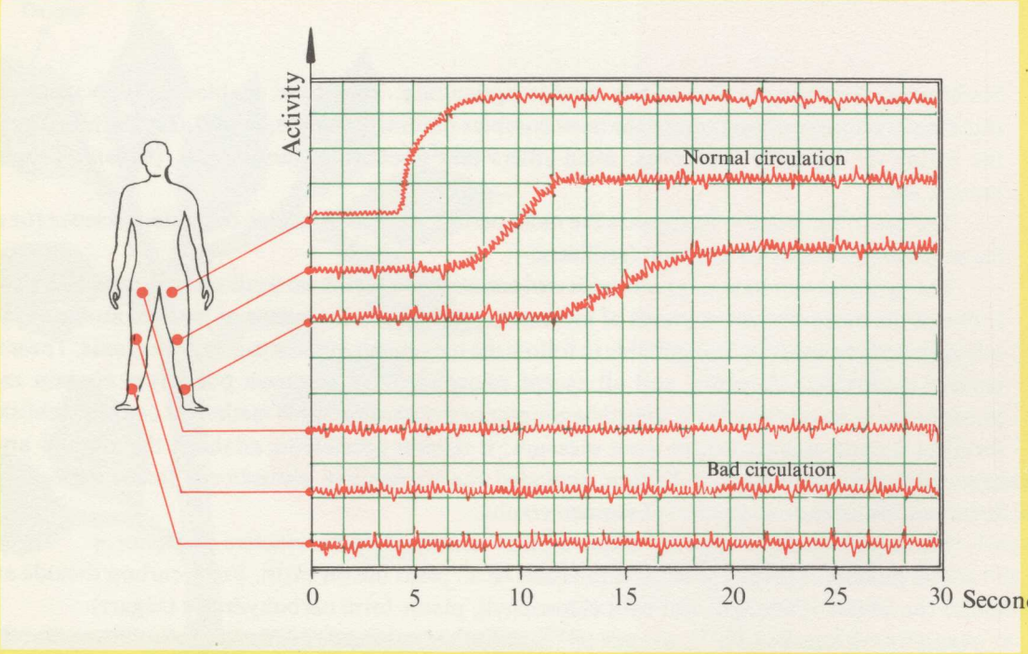
Radioactive isotopes are also used to study the speed of blood circulation. By marking one point in the blood circulation with radioactive isotopes, it can be traced, examined and measured.

The bottom illustration on the opposite page demonstrates the use of sodium 24 which has been found useful in diagnosis and treatment. The half-life of sodium is about 15 hours, and it is therefore useful in the analyses of processes which take place in the organism.

In diagnosis of constriction of the blood vessels, the following method is adopted: a small dose of sodium chloride, marked with sodium 24, is injected into the vein of the forearm, then a G.M. counter is placed against the leg. If the blood circulation is normal, activity is very soon registered in the leg, increasing to maximum in an hour. If activity increases too slowly, it means that circulation is defective.



Localization of a brain tumour by means of two scintillation counters. The counters register gamma rays from radioactive arsenic 74 deposited in the tumour. The point of intersection of the lines connecting the counters, where they register the highest number of coincidences, indicates the location point of the tumour.



Analysis of blood vessel constriction by means of radioactive sodium 24.

USE OF RADIOACTIVE ISOTOPES IN AGRICULTURE

Radioactive isotopes are also widely used in agriculture. They have enabled us to increase our understanding of photosynthesis, one of the most complex natural processes, as well as of the nutrition of plants, the action of vegetable hormones, weed-killers and insecticides, antibiotics, parasitic fungi, harmful insects, etc.

The use of radioactive isotopes is the most perfect method available to modern science for analysing the nutrition of plants by artificial fertilizers.

The artificial nutrition of plants with various minerals (artificial fertilizers, nitrates and phosphates), is one of the most efficient methods of increasing production. By means of marked atoms of radioactive nitrogen and phosphorus, it is possible to follow the movement of these minerals in plants. These fertilizers contain radioactive elements, and all except phosphorus or common potassium contain radioactive phosphorus or potassium. With a particle counter or the photographic method, it can be established which fertilizer a plant utilizes and in what measure; it is even possible to establish the amount and time of absorption through trunk or foliage, provided the radioactive phosphorus forms deposits in leaves, branches, fruits and seeds, and subsequent results.

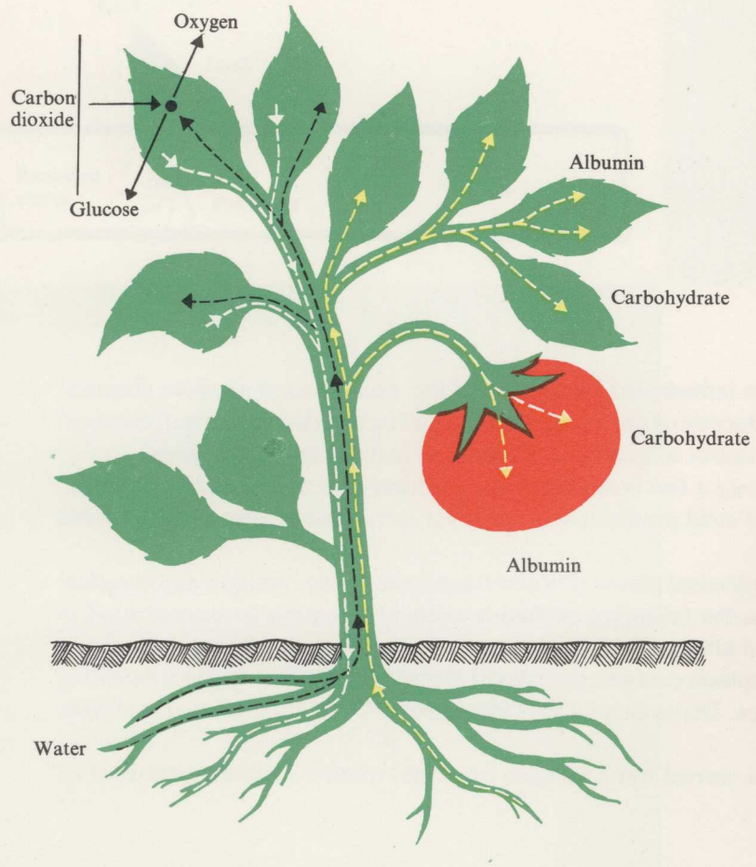
The top illustration opposite shows a plant nourished on radioactive phosphorus.

The process of photosynthesis is the basis of all plant life on earth. From carbon dioxide and water, under the action of sunlight and with chlorophyll, plants form carbohydrates (sugars).

Analyses with carbon (C^{14}), oxygen (O^{17}) and other radioactive isotopes, have shown that the oxygen released during photosynthesis derives from water and not from carbon dioxide, and that the sugar of fruit and berries is formed in measurable quantities only after several seconds of illumination. If the plant is illuminated with a red-yellow light, mainly carbohydrates are formed; with a blue light, albumins, etc.

The bottom illustration opposite shows the process of photosynthesis, that is, the results obtained by using radioactive isotopes.

Radiographs of a plant grown in earth fertilized with radioactive phosphorus. The dots on the leaves indicate the presence of radioactive phosphorus.



From carbon dioxide and water, the plant forms carbohydrates (the sugar of berries and fruits) from which starch is derived. From the carbon dioxide, water, ammonia, phosphorus and metallic salts are formed the amino acids which are the basis of the albumins.

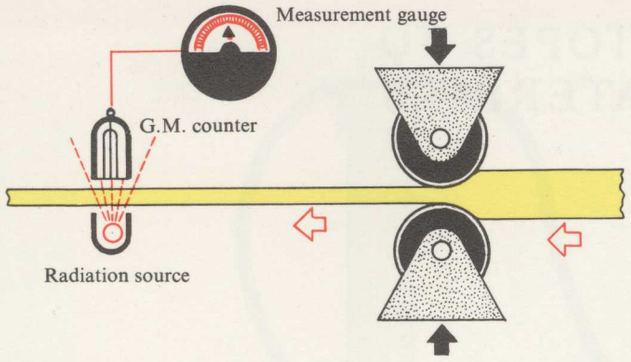
USE OF RADIOACTIVE ISOTOPES IN INDUSTRIAL MEASUREMENT

Radioactive isotopes are widely used in industry for the analysis of the mechanism of physical, chemical and technological processes in the production of steel, coal, naphtha and its derivatives, cement, chemical products, corrosion of materials and control of quality, dimensions of component products, etc.

The illustrations opposite show only a few examples of the practical uses of radioactive isotopes: measurement of thickness, counting of solid products on a conveyor belt, measurement of fluid speeds and levels in containers.

To obtain information vital in mechanical production about mechanical wear and tear and chemical corrosion of important machine parts, the following method is adopted: the piece to be controlled is marked with a radioactive isotope and after greasing with plenty of oil, the piece is made to function. The oil which drips into a separate receptacle contains particles of the piece under examination, including those containing the radioactive isotope. Depending on the radioactivity of this oil, the amount of wear and tear can be calculated.

With this system, controls can be carried out on engine cylinders, friction surfaces, behaviour of lubricating oils, etc.

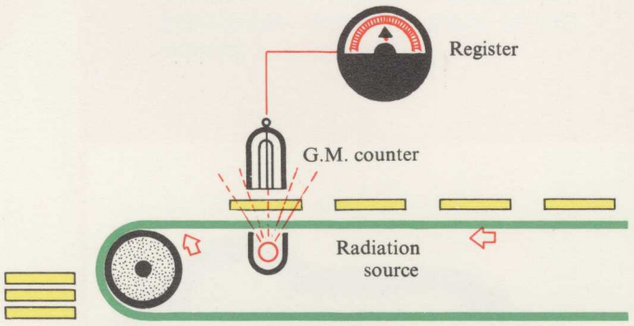


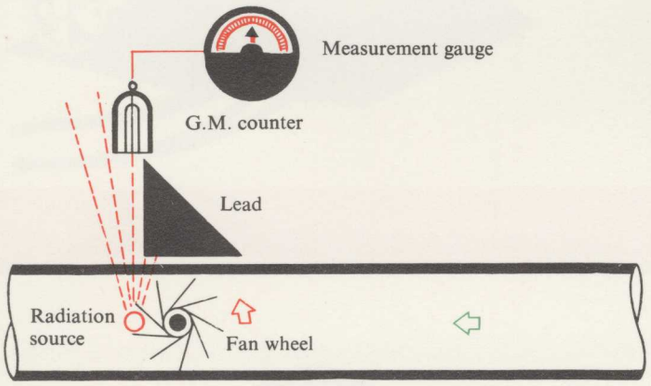
Measurement of a conveyor belt thickness

This method establishes the thickness of a conveyor belt. The intensity of radiation depends on the thickness of the material. It is read with a special instrument. Measurement is continuous, the material may have various thicknesses, different combinations, states, etc. Measurement neither damages nor interrupts production processes.

Count of mass products on conveyor belt

The product passes through a shaft of rays, that is, between source and counter. Each product thus causes an interruption or lowering of intensity of this stream, and this is registered on the electrical counter. The instrument may be attached to an automatic packing machine; this will begin work when the number of objects to be packed is complete (e.g. cigarettes, pills).



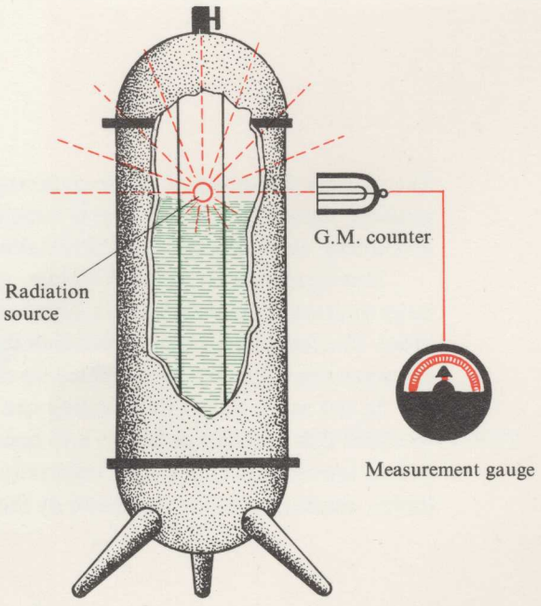


Measurement of the speed of a fluid

A special fan wheel is placed in the tube, with the radioactive source on one of its blades. Between source and counter there is a lead absorber, so that the counter sees the source only in a given position of the blade. With the circulation of the fluid, the fan wheel rotates and at every rotation, the source strikes the counter. The speed of the fluid corresponds to the frequency of the wheel's rotation.

Measurement of fluid level in a container

The ball-cock floating on the surface of the fluid contains the radioactive source. Its position, that is its depth, may be established with the counter. Thus the depth of liquid in the container corresponds to this measurement.

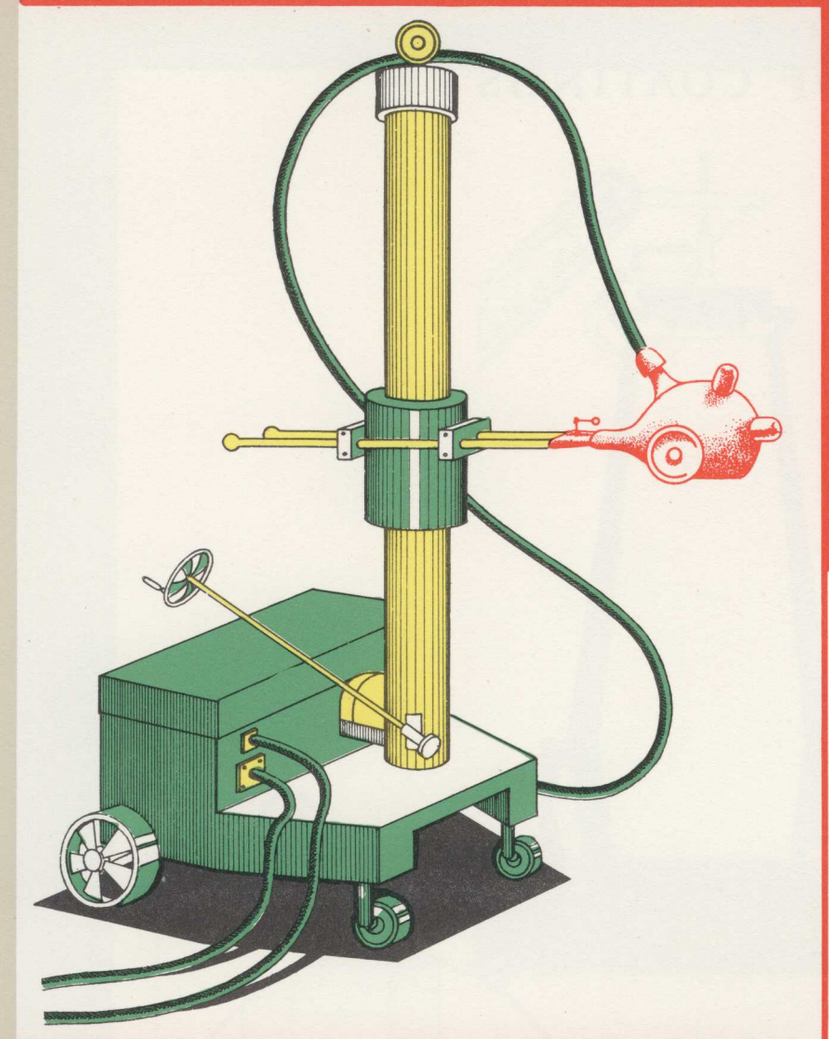


USE OF RADIOACTIVE ISOTOPES TO DISCOVER DEFECTS IN MATERIALS
(gamma defectoscopy)

The gamma defectoscope is the apparatus used for controlling the casting and welding of metals. This method, based on gamma rays, is widely used in various branches of industry, in the construction of machinery, ships, bridges, and in metallurgy.

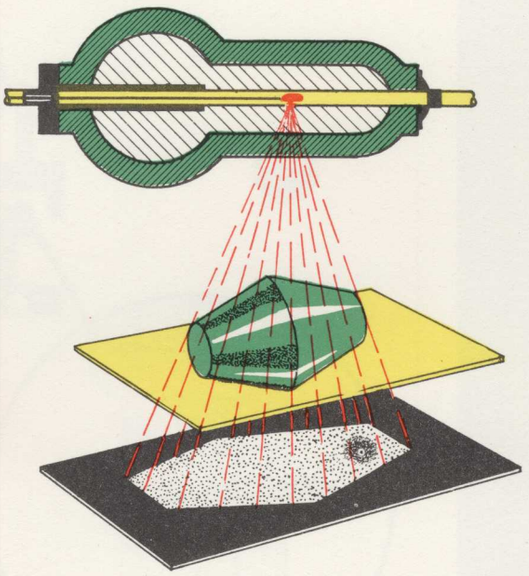
During metal casting it can happen, and often does, that the casting is not homogeneous, but contains holes or cracks. These defective points will cause the piece to break up. The defectoscope is used to detect these. The test piece is placed between the source of radiation and a photographic plate; after a certain exposure time, the defects will show up on the developed plate in the form of darker patches.

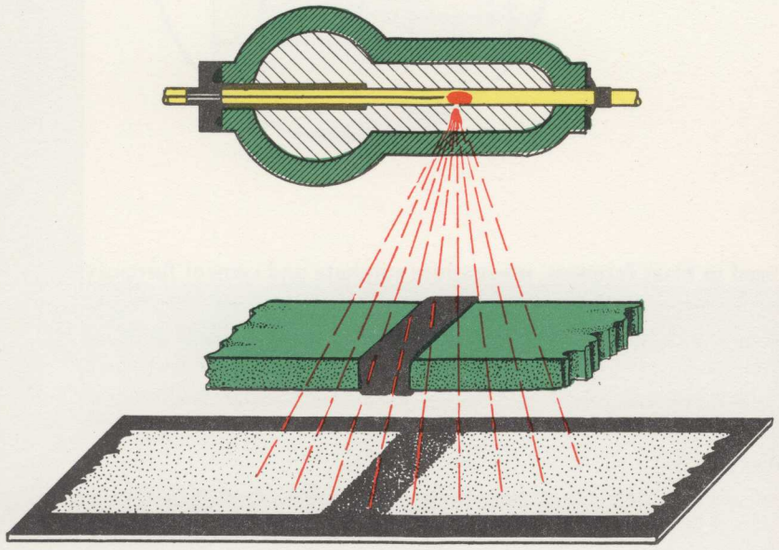
In the same way metal welding can be controlled. The testing can also be done with a radiation counter. The radioactive source and counter are fixed in position, while the object, placed between the two, is moved slowly and with regularity. Since the radiations penetrate the defective parts more easily (holes, cracks), these are registered by the counter as higher intensity transmissions received.



General appearance of gamma apparatus for controlling casting and welding in large metal sections

Control of the quality of casting. The photograph reveals a cavity in this welding





Control of the quality of soldering

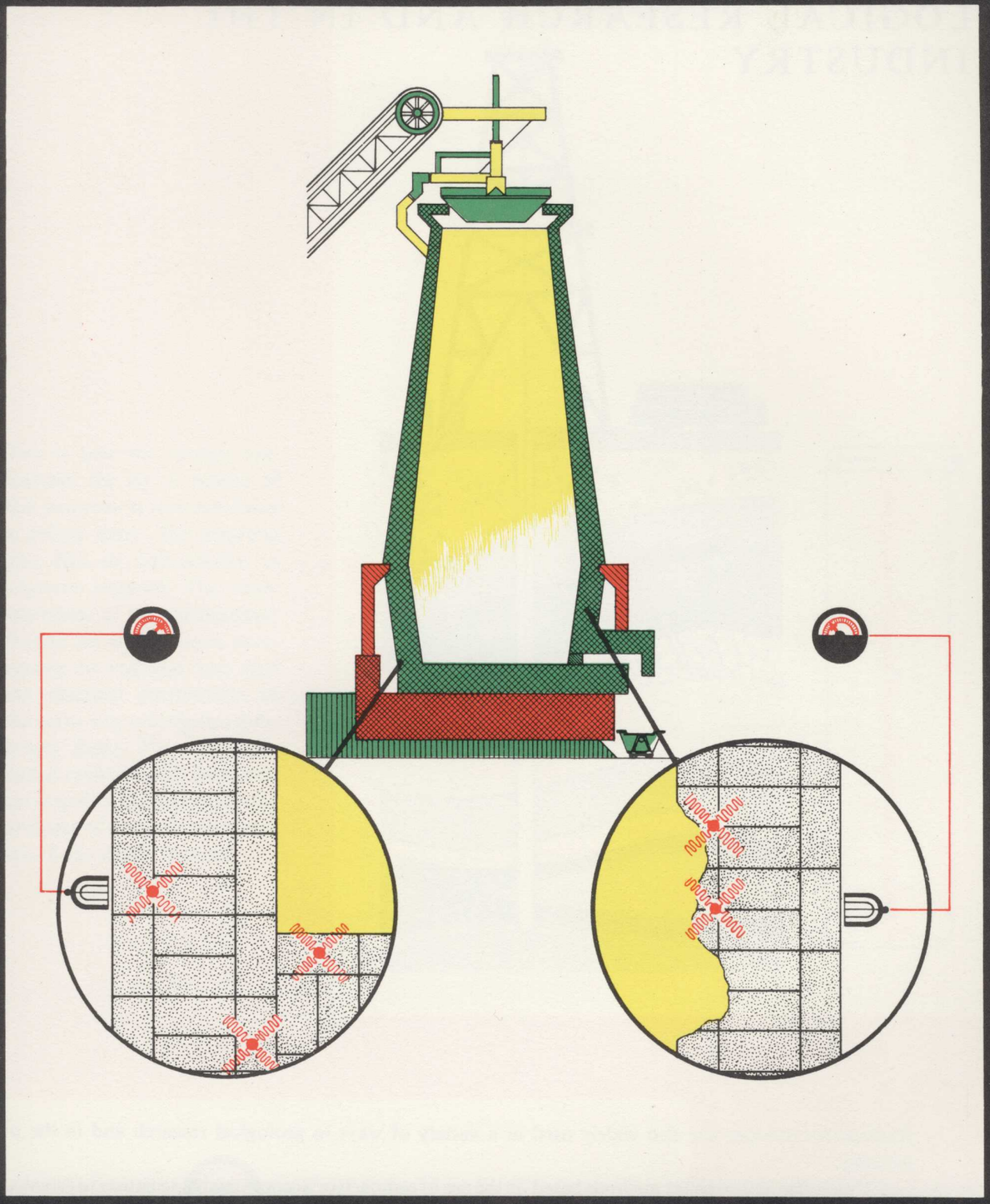
USE OF RADIOACTIVE ISOTOPES TO CONTROL FIRE-PROOF COATINGS

Radioactive isotopes are successfully used in blast furnaces, magnesium sulphate and cement furnaces, etc., to detect and localize defects in the fire-proof coating or lining.

In furnace building, ampoules containing radioactive sources (e.g. cobalt 60) are placed at differing depths in the lining. Their intensity, after passing through the lining, is registered by a radiation counter. The isotope conserves its radioactive emission intensity unaltered for as long as the furnace lasts, because of its long half-life.

When the melted metal damages the first layer of lining, the ampoule nearest the surface is carried away, and thus the counter will register a decrease in radiation intensity. The disappearance of the last ampoule indicates that the whole lining has suffered enough wear and tear to need changing.

Radioactive sources may therefore be utilized in tough physical and chemical conditions, in this specific case, at extremely high temperatures.



In blast furnaces the control of fire-proof linings or coatings is made with cobalt 60 or some other gamma emitter.

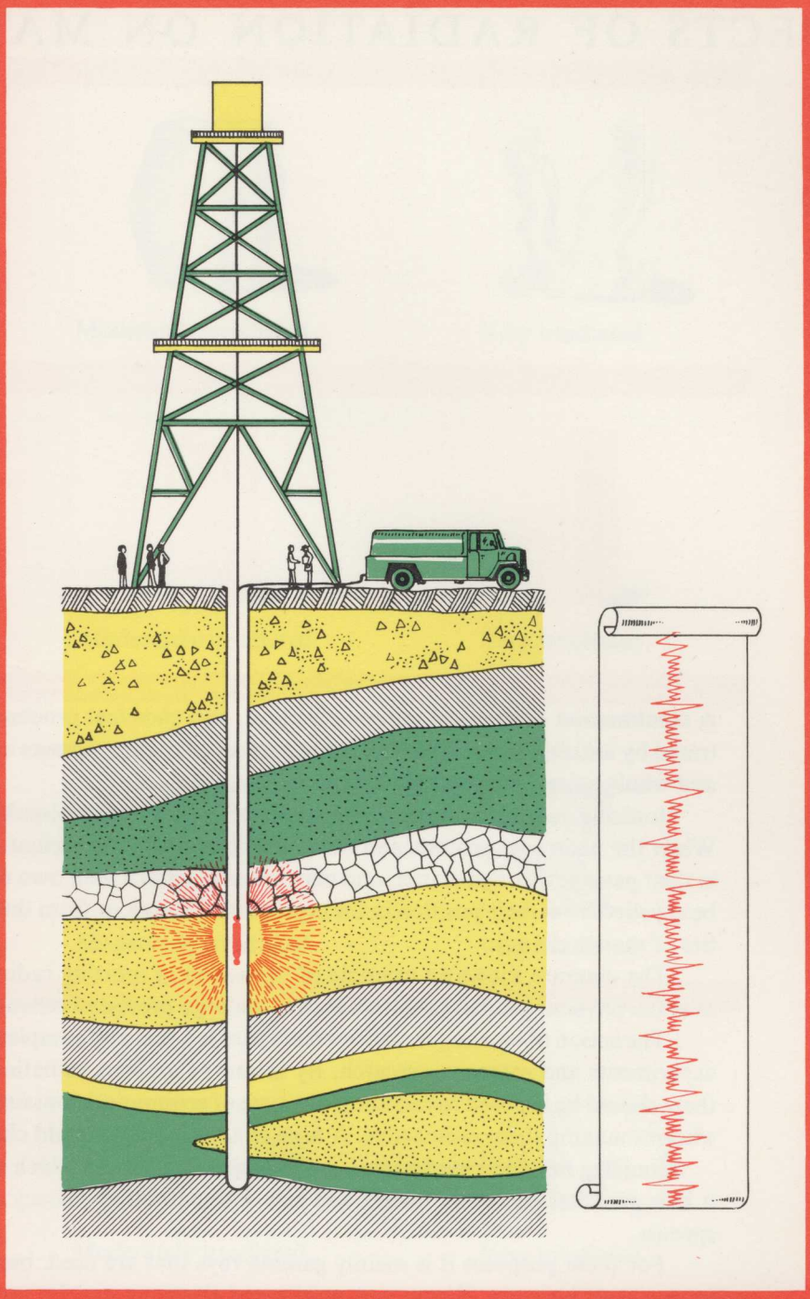
USE OF RADIOACTIVE ISOTOPES IN GEOLOGICAL RESEARCH AND IN THE OIL INDUSTRY

Radioactive isotopes are also widely used in a variety of ways in geological research and in the oil industry.

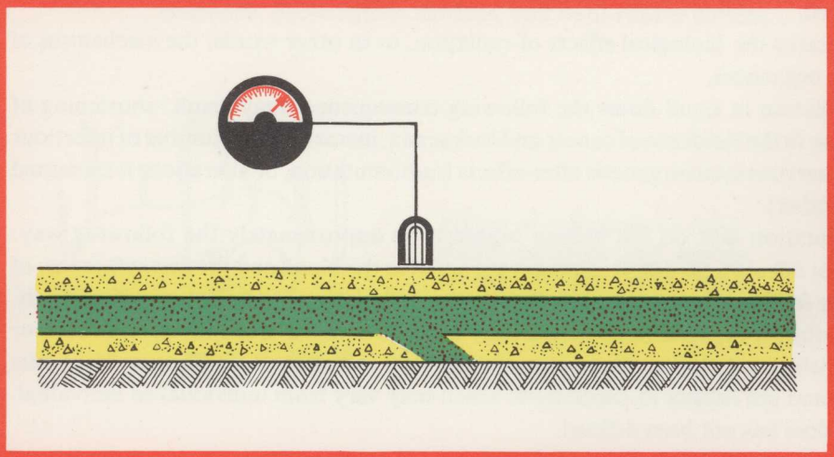
Numerous and complex methods based on the use of radioactive isotopes enable scientists to establish the chemical elements which compose separate geological strata of the earth at differing depths. As the illustration shows, a source of fast neutrons (usually radium-beryllium and polonium-beryllium) is lowered down a drilled shaft; through nuclear reactions the neutrons cause radioactivity in surrounding matter, and thus, depending on the specific characteristics of this radioactivity, the composition of the stratum under study can be established.

The same procedure is followed to locate oil fields, and it is possible not only to draw conclusions as to the nature of the hydrogen in adjacent rocks, but also to distinguish the hydrogen of water from that of oil.

In the oil industry, radioactive isotopes are also used to discover possible breakages in pipelines underground.



This is how the 'atomic eye' searches for oil. A source of fast neutrons is lowered down a drilled shaft. The neutrons give rise to radioactivity in adjacent material. The characteristics of the radioactivity depend on the elements composing the material, and thus the chemical composition of the earth may quickly be established. *Right:* The tape registering radioactivity; determinate impulses correspond to the presence of determinate materials in the drilled ground.



The discovery of breakages or leakages in oil pipelines is done by introducing a radioisotope into the pumped oil and following its course. The breakage is found where the intensity of radiation decreases rapidly.

EFFECTS OF RADIATION ON MATTER

A combination of physical, physio-chemical, and chemical processes occurs in matter when it is penetrated by ionizing radiations. The consequences of these processes are changes in the cells, tissue, organs and whole animal or vegetable organism.

Ionizing radiation changes the order of atoms and molecules in the structure of the elements. When the neutrons, protons and other particles possess sufficient energy, they collide with the atoms in their passage through matter, and may transmit part of their own energy to them, so that the atoms may be expelled from their position in the crystalline network or from the molecule. Consequently the properties of matter change.

The diagram shows an example of the action of ionizing radiations on plastic matter; in it we see how the physical properties of this matter undergo profound alterations.

The action of ionizing radiations on matter is a vast and complex problem, still a subject of numerous experiments and extensive research. By means of ionizing radiation, food products can be conserved; these should be exposed to radiation in a type of economical container or package, which conserves them without making them radioactive. A high irradiation dose could change the flavour of the food.

Ionizing radiation renders inactive the micro-organisms which would otherwise cause deterioration; it kills parasites and other insects and acts with particular efficacy in the destruction of tuber shoots or sprouts.

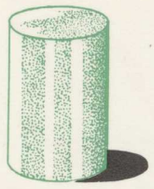
For these purposes it is mainly gamma rays that are used, because they are more penetrating and economical; however, X-rays and accelerated electrons may be used too. At present it is thought that, for practical purposes, small and medium doses of irradiation are more suitable. But the fact remains that the problem of food conservation by means of radiation is still full of unknown factors and thus subject to further study and research.

Another question concerns the biological effects of radiation, or in other words, the mechanism of ionizing action in all living organisms.

From prolonged irradiation in small doses the following consequences may result: shortening of life and early ageing, increase in the incidence of cancer and leukaemia, increase in the number of infectious diseases, exhaustion of the nervous system, genetic after-effects (radiomutation, or alterations transmitted from one generation to another).

Irradiation of brief duration acts on the human organism in approximately the following way: 50R: working capacity is not affected. 50–100 R: changes are noted in the blood and the first symptoms of illness are felt, but aptitude for work is not lost. 100–200 R: the pathology of radiation manifests itself, and a certain number of subjects exposed to radiation may become unfit for work for several days or weeks. 200–400 R: illness, which is lethal in 50 per cent of cases. 600 and more R: fatal dose. The limits indicated are not absolute and are subject to oscillations which may vary from individual to individual. In fact the minimum fatal dose has not been defined.

PHENOLS

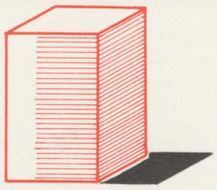


Non-irradiated

Moderately irradiated

Very irradiated

POLYSTYRENE

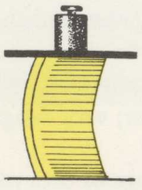


Non-irradiated

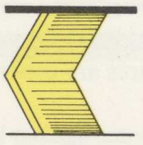
Moderately irradiated

Very irradiated

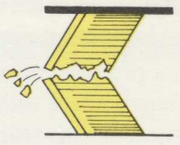
POLYETHYLENE



Non-irradiated

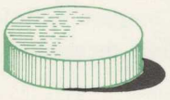


Moderately irradiated



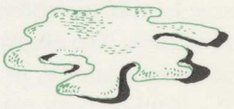
Very irradiated

BUTIL-RUBBER



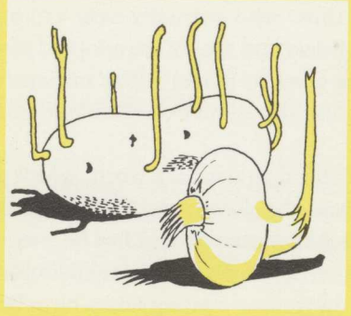
Non-irradiated

Moderately irradiated

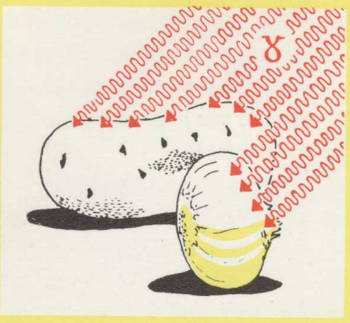


Very irradiated

Action of ionizing radiations on plastic materials: phenols dilate, polystyrene contracts, polyethylene hardens, and butil-rubber softens.



Effects of radiations on food-stuffs: potatoes and onions do not produce shoots for a very long time.



PROTECTION FROM IONIZING RADIATIONS

As we see in the illustrations, there are various ways of defending oneself against ionizing radiations. Anti-alpha shields are used as protection from alpha rays. Since the range of alpha rays in the atmosphere is very short and they can be stopped by a sheet of paper or thin layer of any material, they do not constitute a problem where protective measures are concerned; they are, however, very dangerous if they come into contact with an organism.

Anti-beta ray shields are used as defence against beta rays. Since the range of beta particles in air reaches up to a metre, aluminium or plastic shields are used for protection. Beta rays are especially dangerous to the eyes.

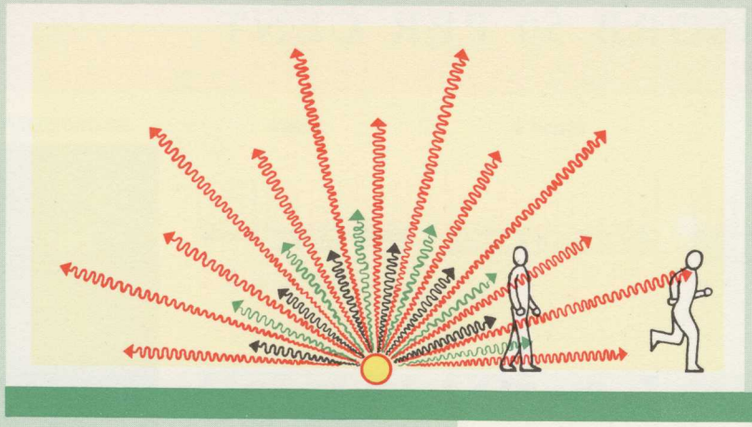
Anti-gamma ray shields must be built of materials containing elements with high atomic numbers, capable of absorbing gamma rays. Iron, lead and steel are commonly used to absorb gamma rays, as well as other, more economical materials, such as water, concrete, gravel, etc. During absorption of gamma rays by this protective shield, three processes occur: photoelectric effect, Compton diffusion, and pair formation. The absorption of gamma rays depends on the energy of the quanta themselves, and also on the atomic number of the absorbent material.

Anti-neutron shields must be built of materials containing elements with low atomic numbers, because these slow down and absorb neutrons. Usually materials containing hydrogen, water, paraffin, etc., are used. The absorption process where neutrons are concerned may be divided into two stages: slowing down of high energy neutrons as a result of elastic or inelastic diffusion, and capture of those slowed down. In the process of capture, high energy quanta are usually emitted; this phenomenon requires a supplementary protection made of materials with high atomic numbers.

To protect the eyes from alpha rays and weak beta rays, normal spectacles are adequate. But for higher energy beta rays, special lenses are used (e.g. organic silicates, plexiglass, 2–2·5 mm thick). Lead glass and tungsten phosphate glass will also give protection against gamma rays. Against neutrons, lenses of cadmium borosilicate and fluorine compounds are necessary. For those who normally wear ordinary spectacles, a second pair is needed. To protect the respiratory organs, filters and masks are adopted along with other suitable apparatus. For the protection of the body during work in places where radioactive dust or gas is present, special plastic overalls are worn, of polyvinyl chloride, about 0·75–0·80 mm thick, for example.

To protect the hands from radiations, surgical rubber or vinyl chloride gloves are worn, which are adequate against alpha and weak beta rays. If greater energies are involved, the gloves must be impregnated with lead. Leather gloves or other materials which absorb liquid and gather dust should not be used.

There are also chemical methods of defending the organism from certain radiation doses (Becaptam, AET) provided these are used immediately. However, in some cases dangerous consequences have been known, such as growth of tumours, arrested growth, etc.

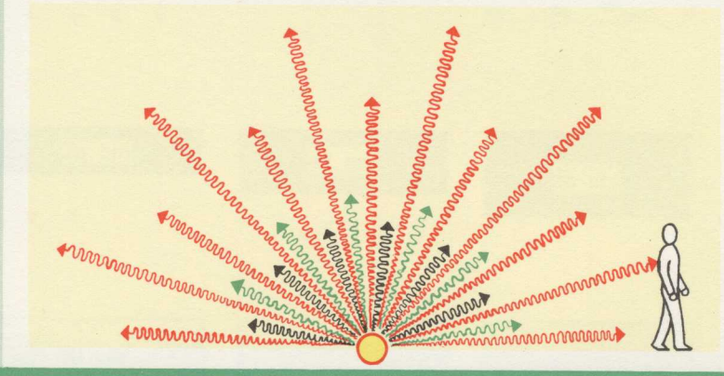


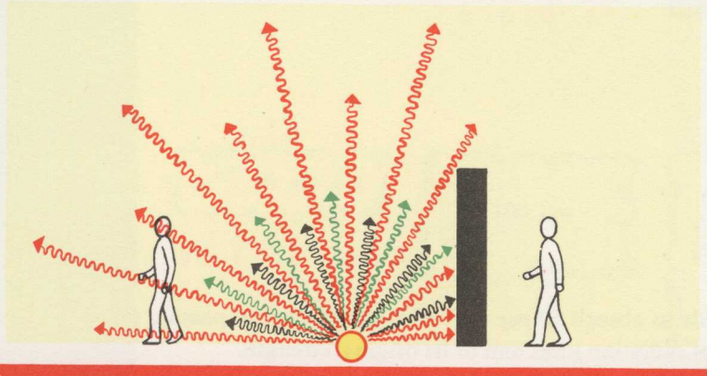
Defence time

The shorter the time of exposure to the source, the smaller the dose of radiation. The dose absorbed is proportional to the time of exposure to the radioactive source.

Defence distance

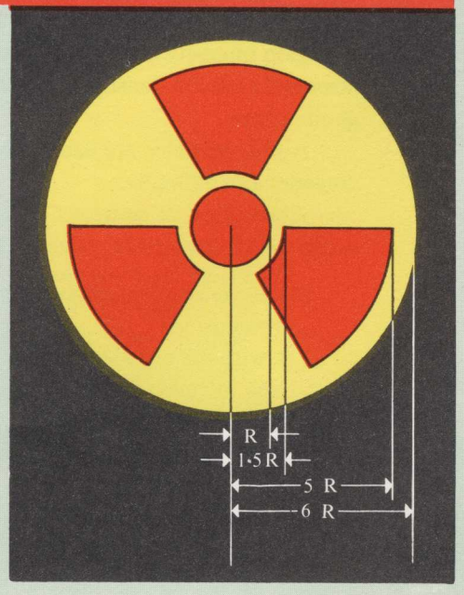
The greater the distance, the smaller the radiation dose. The intensity of radiation is inversely proportional to the square of the distance, like light.





Defence screen

The thicker the protective shield, the smaller the radiation dose. Protective materials are concrete, steel, iron, lead; these absorb or weaken the radiation.



Radiation danger signal

This signal is used to indicate objects, spaces, clothes, instruments, materials, etc., inside or outside which the danger of radiation exists or is possible. The size of the signal is proportional to that of the object, apparatus, etc., to which it is attached.

SHIELDS WHICH ABSORB 50 PER CENT OF RADIOACTIVITY

Various materials are used as shields to absorb 50 per cent of radioactivity; in passing through a layer of a certain material, the intensity of radiation loses half of its original strength.

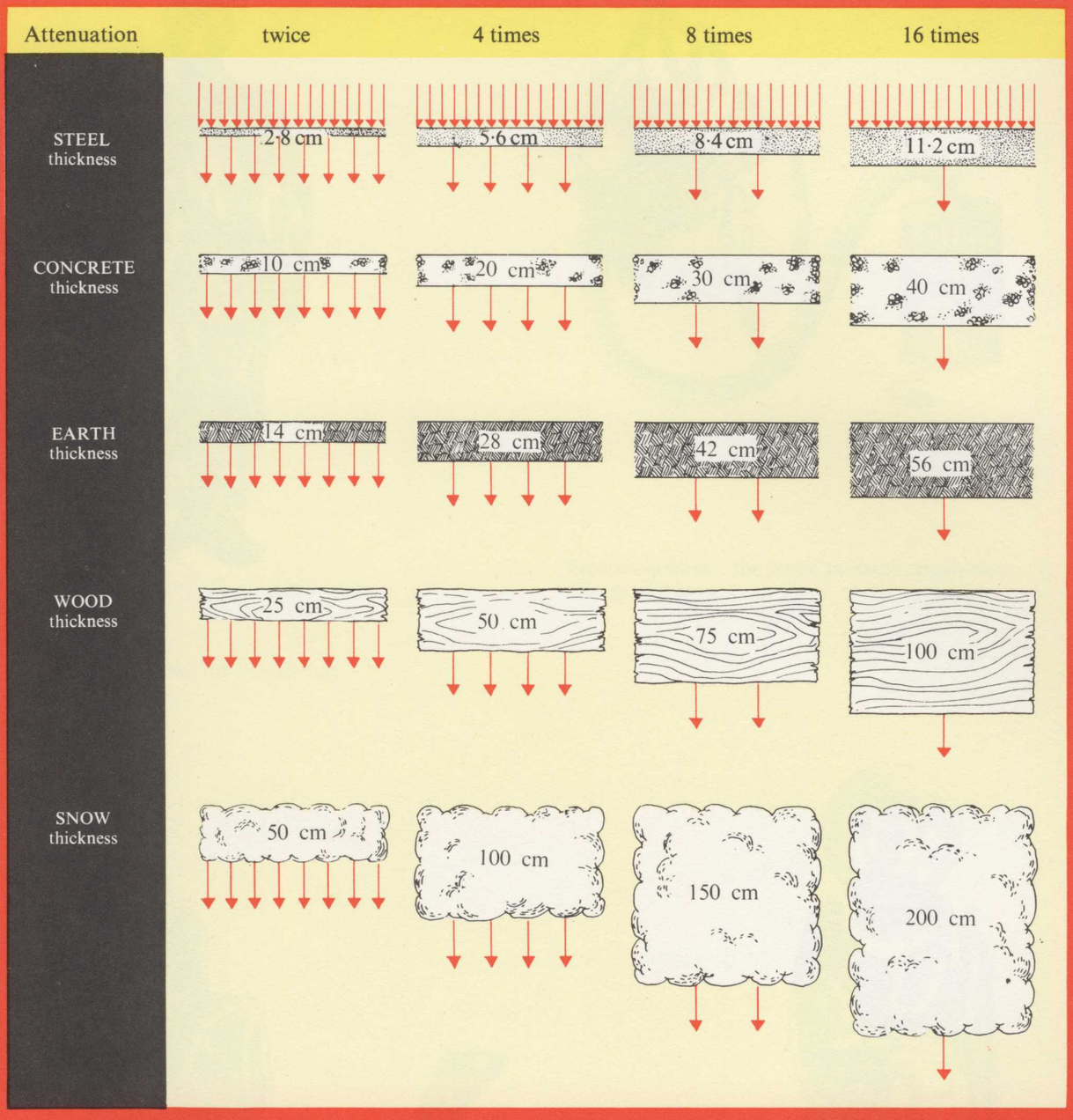
The requisite thickness of a shield depends on the nature of the material used, on the type and energy of radiation, and is more or less inversely proportional to the density of the material. The decrease in radiation intensity occurs because the radiation is absorbed in part by the material. Absorption depends essentially on the density and composition of the material used, and on the energy of the particles or gamma rays.

Alpha particles are easily absorbed, beta ones with greater difficulty, and gamma rays only with considerable difficulty.

Absorption of neutrons occurs through their capture by nuclei and the formation of new unstable nuclei which transmute, passing to the stable state. This development may come about in three ways:

(1) the unstable nucleus is a beta-emitter; the energy of decay is irradiated with electrons and gamma radiations
(2) with the expulsion of the low energy neutron. A part of the energy of these neutrons is absorbed as intrinsic energy of the nucleus, and afterwards emitted as gamma radiation (this process is called inelastic diffusion of neutrons)
(3) the fission of the nucleus into two fragments with simultaneous emission of neutrons and gamma quanta.

On the basis of theoretical calculation and practical experiment, the thickness of various materials capable of halving radiation of various types can be established, as indicated in the diagram opposite.



This figure shows the thicknesses of materials most commonly used in the building of primary atomic antiradiation shields, sufficient to reduce the intensity of primary gamma radiations or neutron ones to half (first column), to one-quarter (second column), one-eighth (third column), one-sixteenth (fourth column). The measurements referred to in the figure are for use against neutrons and gamma rays of average energy, emitted in fission.

Shields which absorb 50 per cent of radioactivity

PROTECTIVE EQUIPMENT

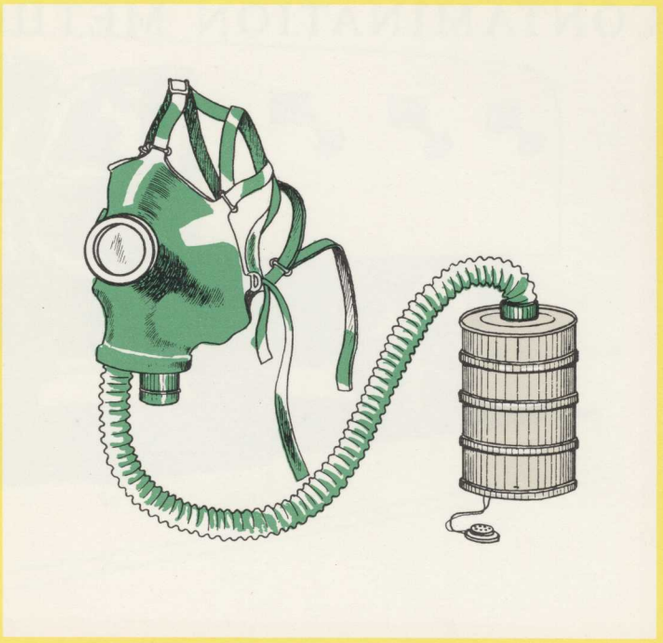
Protective equipment is designed for defence against radioactive contamination wherever it is contracted, whether in laboratories or during atomic explosions. It takes the form of:

(a) *filters:* that is, masks or apparatus to protect the respiratory organs, eyes and face from radioactive dust and other poisonous materials
(b) *insulation:* overalls, gloves, boots, trousers, socks, impermeable coat, etc., to protect the skin and body.

These protect the body from the lower energy radiations (alpha rays – weak beta rays), from radioactive dust and from other dangerous materials; they may be fabricated from rubber, rubberized canvas, plastic material or other suitable materials.

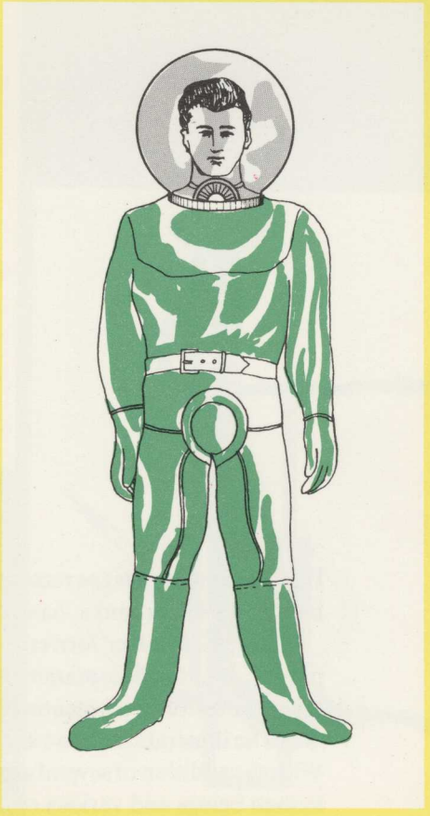
The illustration shows a few articles of such equipment. Among other means of preventing penetration of the organism by radioactive material are ventilation systems, manipulators, etc.

Decontamination overall suit



Protective filters: the mask protects respiratory organs and eyes.

Protective insulation: the overalls with hood, gloves and boots protect the body from radioactive dust and biological and chemical agents.



For work in contact with radioactive materials, this type of plastic suit is worn.

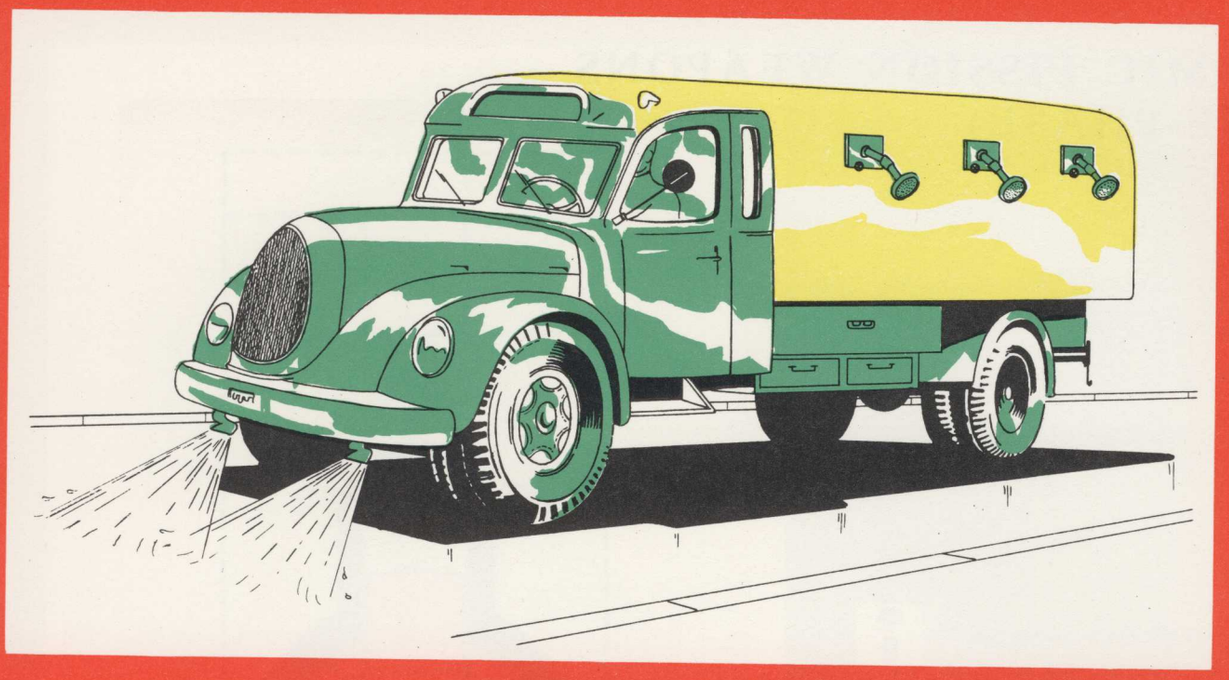
DECONTAMINATION METHODS

Decontamination is the removal of radioactive waste from human beings, objects and the earth. Methods include sprinkler tanks, hand and motor pumps, baths and portable apparatus.

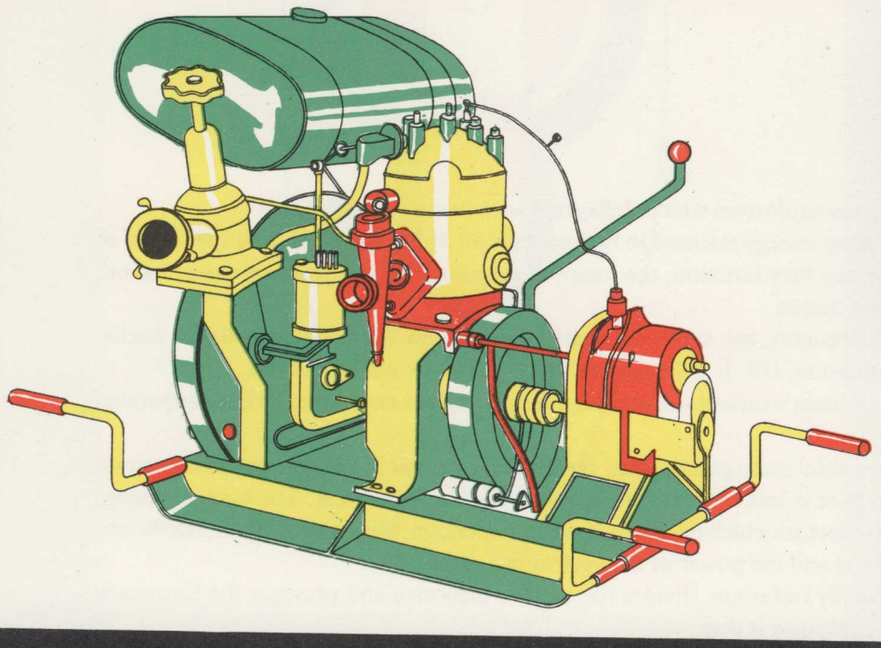
Water-sprinkler lorries and cleansing carts in normal use may also be adopted, as may automatic pumps, etc., for decontamination work. The radioactive waste must be removed to a place where it no longer constitutes a potential danger.

The illustration shows a sprinkler lorry for the decontamination of hard surfaces, land and buildings. With the addition of several special gadgets such as tubes, heaters, etc., it can also be used to decontaminate human beings and various objects.

The methods indicated make use of water and other liquids; other means may be adopted for removing radioactive dust particles, for example vacuum or suction cleaners, gravel, water vapour, alkalis, acids, organic solvents, soaps, detergents, etc.

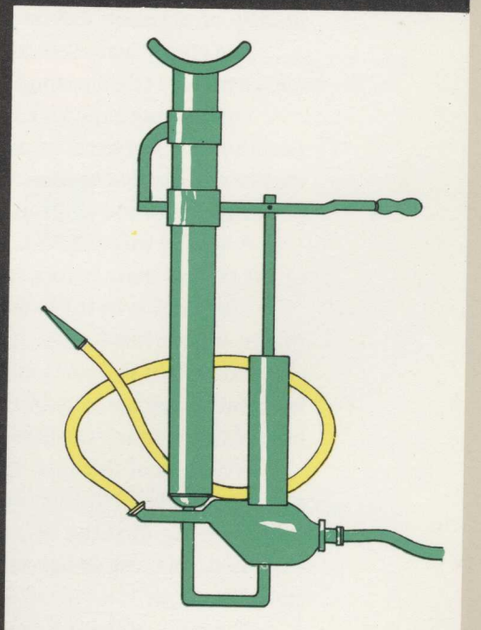


Decontamination sprinkler lorry



Decontamination motor pump, transportable

Decontamination hand pump



Decontamination workmen must wear protective clothing

ATOMIC FISSION WEAPONS (ONE-PHASE)

The term 'atomic weapons' means explosives which deflagrate with nuclear reactions.

These weapons use the nuclear energy released in fission reaction of heavy nuclei or in the fusion of light atoms. Depending on the way they function, the weapons may be divided into three types: fission, fission-fusion, and fission-fusion-fission.

In the first type of atomic weapon, the explosive energy is based on the fission of atomic nuclei, usually of uranium 235 or plutonium 239. It is known as the A bomb or nuclear bomb.

The constituent elements of these weapons are nuclear charge (nuclear explosive), primer apparatus and container (shell casing).

The nuclear explosive has a total mass greater than the critical one, but is divided into two or more parts so that the mass of each part is less than the critical one, that is, subcritical. The nuclear charge may be surrounded by neutron reflectors which diminish neutron dispersion, thus increasing the coefficient of utilization of the fissile material and the power of the explosion.

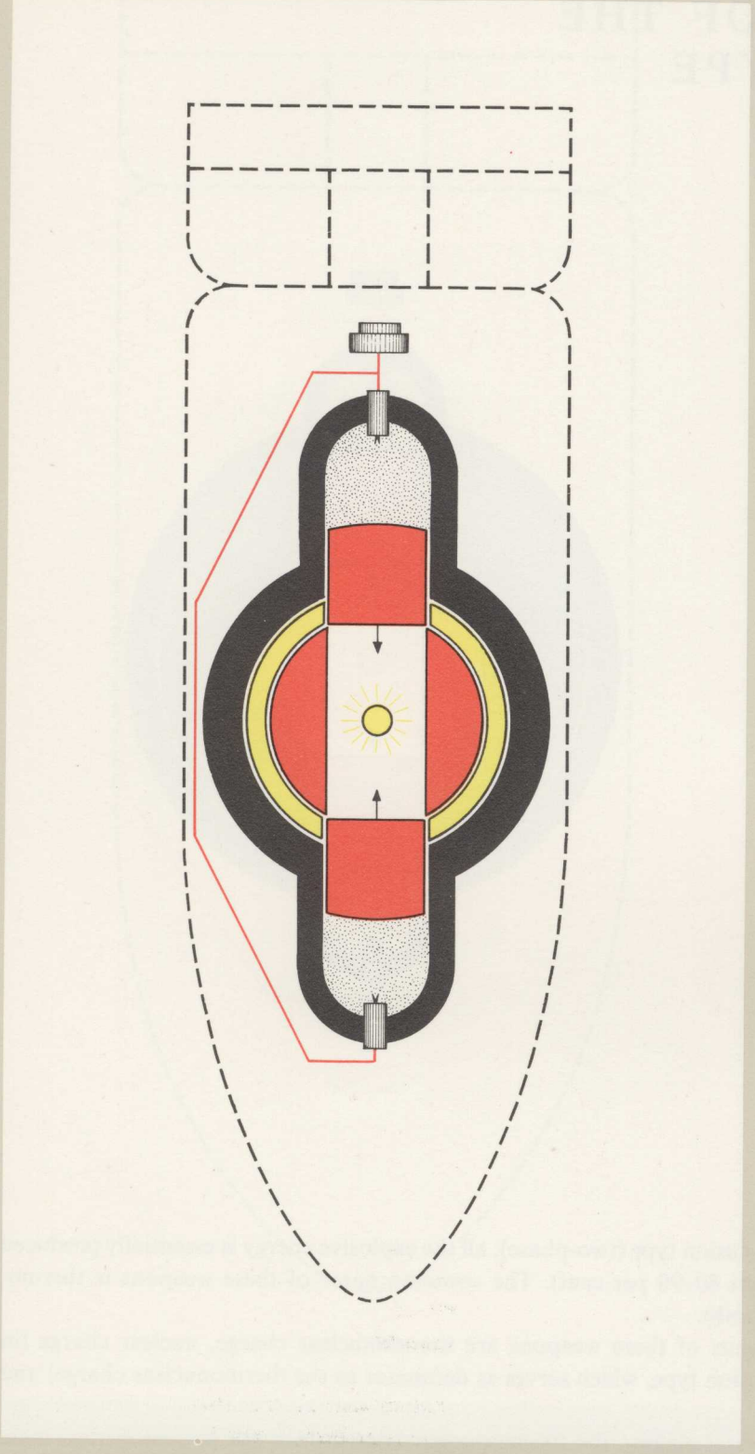
A special safety device, usually cadmium, divides the nuclear explosive and prevents the formation of the critical mass before the explosion is due.

The reunion of the various parts into which the nuclear charge was subdivided, causes the formation of the supercritical mass; thus the explosion occurs, primed by a special device, the detonator. The reunification of the parts must be instantaneous, because the time from start of the chain reaction to the moment of explosion is in the order of millionths of a second. If this does not happen, explosions may take place in which the fissile material cannot be exploited completely.

Weapons of this type can reach a power equivalent to tens of thousands or hundreds of thousands of tons of TNT (trinitrotoluene). The power depends on the duration of the fission process, which influences the quantity of charge which explodes. Usually from about 1·5 to 3 per cent of the charge is exploited; the rest disperses because the casing does not manage to retain the fissile mass in a compact state for longer.

The mass of these weapons may be in the order of hundreds of kilograms or several tons; it depends on the mass of the casing which is built of material with a high mass number and melting point.

Detailed explanations on the fission of heavy atomic nuclei, nuclear chain reaction and critical mass, can be found in the first part of this book under those headings.



Primer apparatus with detonator

Common explosive

Supplementary source (artificial) of neutrons

Neutron reflector

Nuclear charge (nuclear explosive), e.g. uranium 235, plutonium 239

Casing of hard metal

In atomic weapons of the fissile type (one-phase) all the explosive energy is based on the chain reaction of fission in uranium and plutonium nuclei. These weapons may take the shape of air bombs, missiles, etc.

Atomic fission weapons (one-phase)

ATOMIC WEAPONS OF THE FISSION–FUSION TYPE (TWO-PHASE)

In atomic weapons of the fission–fusion type (two-phase), all the explosive energy is essentially produced by thermonuclear reaction (about 80–90 per cent). The common name of these weapons is thermonuclear or hydrogen bomb (H bomb).

The main constituent elements of these weapons are thermonuclear charge, nuclear charge (in reality an atomic bomb of the fission type, which serves as detonator to the thermonuclear charge) and the casing (body shell).

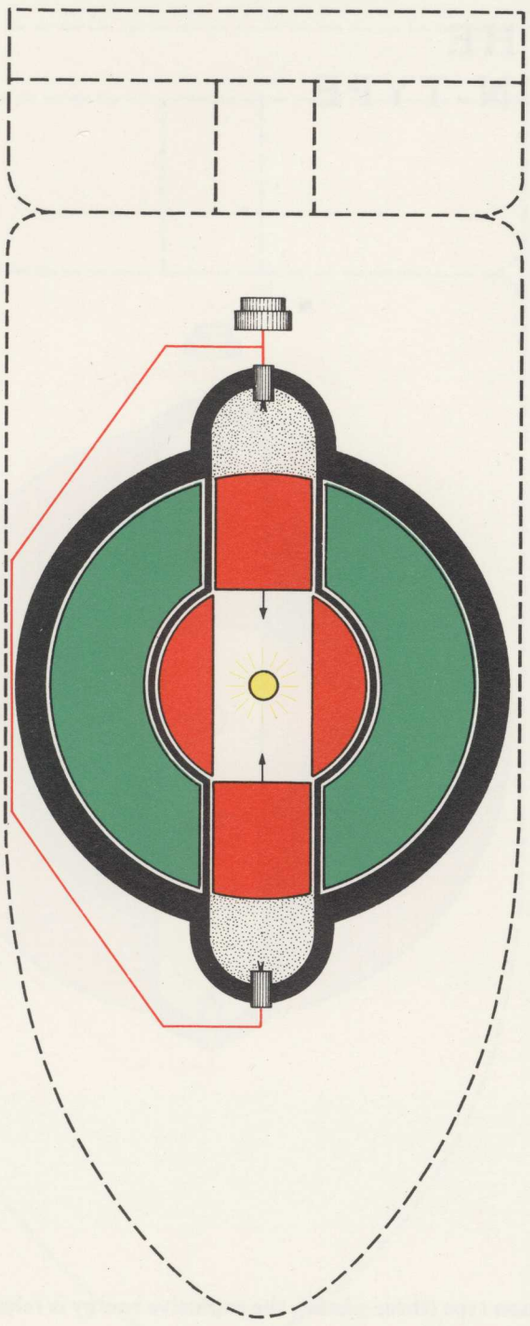
Despite its considerably greater energy, the thermonuclear charge does not possess critical mass and is limited only by the difficulties of 'construction' or by the total mass of the arm. The nuclear charge, which in this case acts as detonator, develops a temperature of tens of millions of degrees in one-millionth of a second, sufficient to prime the thermonuclear reaction.

Therefore, the fission reaction in the nuclear charge takes place first (first phase); once this has created the required temperature, fusion reaction takes place in the thermonuclear charge (second phase).

Weapons of this type may reach a power equivalent to between several thousand and tens of millions of tons of TNT.

For example: 1 g of thermonuclear explosive (lithium + deuterium) can develop an energy equivalent to 66 tons of TNT, 1 kg to 66,000 tons of TNT, etc.

For a detailed explanation of the fusion of light atomic nuclei, turn back to the chapter on the subject in the first part of this book.



Primer apparatus with detonator

Common explosive

Supplementary source (artificial) of neutrons

Nuclear charge (nuclear explosive), e.g. uranium 235, plutonium 239

Thermonuclear charge (thermo-nuclear explosive), e.g. deuterium plus tritium, etc.

Casing of hard metal

In atomic weapons of the fission–fusion type (two-phase), most of the energy (80 per cent plus) is produced by the thermonuclear reaction. An important characteristic of these weapons is the fact that the thermonuclear charge does not possess critical mass, and thus their power is limited only by the difficulties of construction.

Atomic weapons of the fission–fusion type (two-phase)

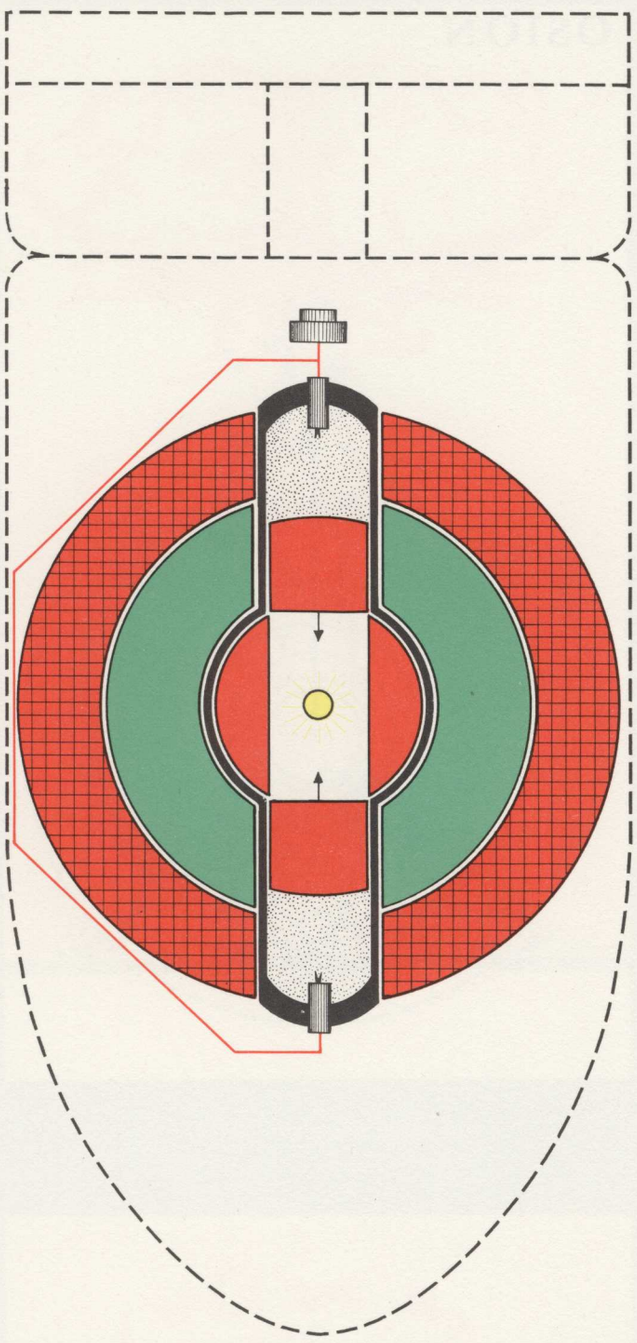
ATOMIC WEAPONS OF THE FISSION–FUSION–FISSION TYPE (THREE-PHASE)

In atomic weapons of the fission–fusion–fission type (three-phase), the explosive energy is released in the process of three successive nuclear reactions.

(1) Fission of heavy nuclei in the nuclear charge: for example, uranium 235, plutonium 239 or uranium 233 (first phase).
(2) Fusion of light nuclei in the thermonuclear charge: for example, deuterium and tritium (second phase).
(3) Fission of heavy nuclei of uranium 238 in the casing cover of the arm (third phase).

The fundamental elements of these weapons are nuclear charge, thermonuclear charge and casing (body shell) of fissile material. The preponderant part of the energy released comes from the fission of nuclei of uranium 238, by the neutrons liberated in the thermonuclear reaction. While uranium 235 easily causes fission provoked by slow neutrons, uranium 238 has a greater collision potentiality for fission with fast neutrons; these are created in the fission of uranium 235 and above all, in the thermonuclear reaction of the second phase.

Utilization of the isotope 238 is the main characteristic of these weapons. They are sometimes known as the uranium bomb (when the casing is of uranium 238), or the cobalt bomb (after explosion, the cobalt casing causes strong contamination), or even the superbomb!



Primer apparatus with detonator

Common explosive

Supplementary source (artificial) of neutrons

Nuclear charge (nuclear explosive), e.g. uranium 235, plutonium 239

Thermonuclear charge (thermo-nuclear explosive), e.g. deuterium plus tritium, etc.

Casing of natural uranium or of uranium 238

In atomic weapons of the fission–fusion–fission type (three-phase), the explosive energy is released in a process which comprises three successive nuclear reactions:

1. Fission of heavy nuclei in the nuclear charge: for example, uranium 235, plutonium 239 or uranium 233 (first phase).
2. Fusion of light nuclei in the thermonuclear charge: for example, deuterium and tritium (second phase).
3. Fission of heavy nuclei of uranium 238 in the casing cover of the arm (third phase).

Atomic weapons of the fission–fusion–fission type (three-phase)

TYPES OF ATOMIC EXPLOSION

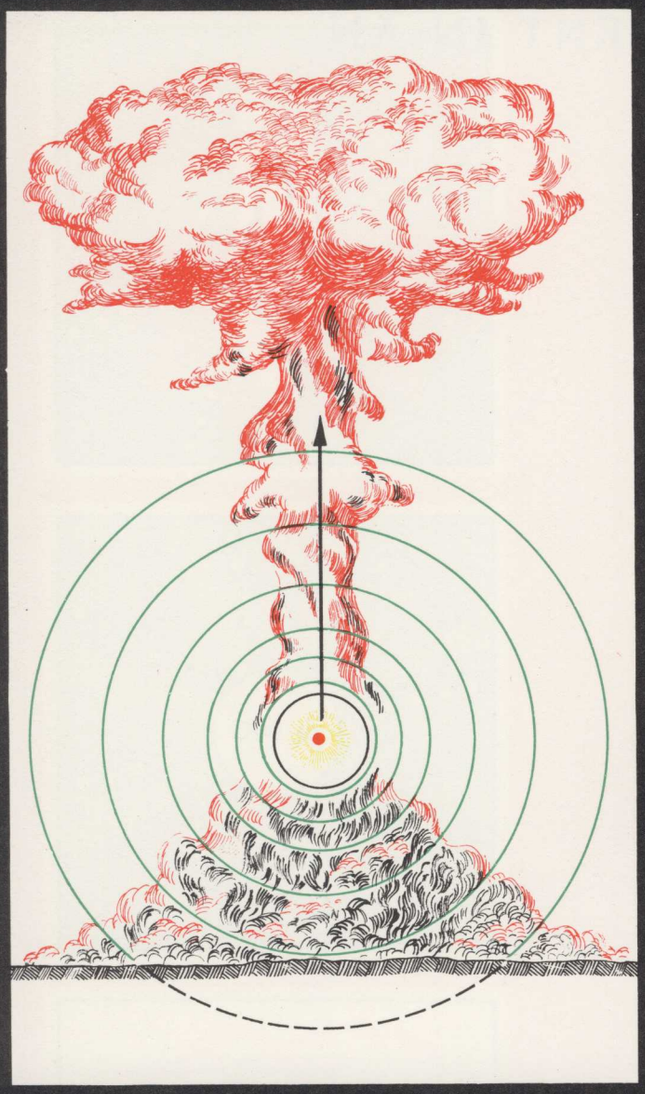
An atomic explosion consists of the instantaneous liberation of an enormous quantity of energy, created as a consequence of one of the reactions: fission (nuclear) or fusion (thermonuclear), which take place in atomic weapons.

The explosion, depending on the type of weapon, scope, power and mode of delivery, may occur in the following ways:

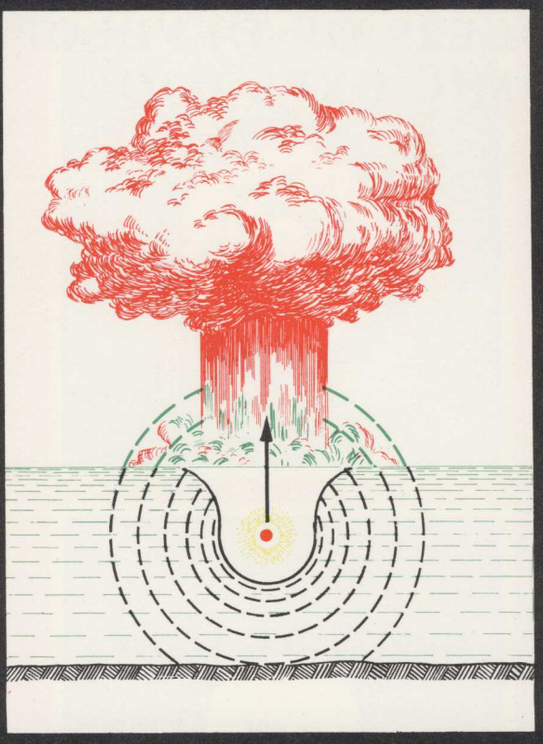
in air, when the sphere of fire or fireball does not touch the surface of earth or sea;
on the surface, when the fireball comes into contact with the surface of earth or water;
underground, at greater or lesser depths beneath the earth's crust;
underwater, at greater or lesser depths in water.

An atomic explosion differs from the conventional type both in power and efficacy.

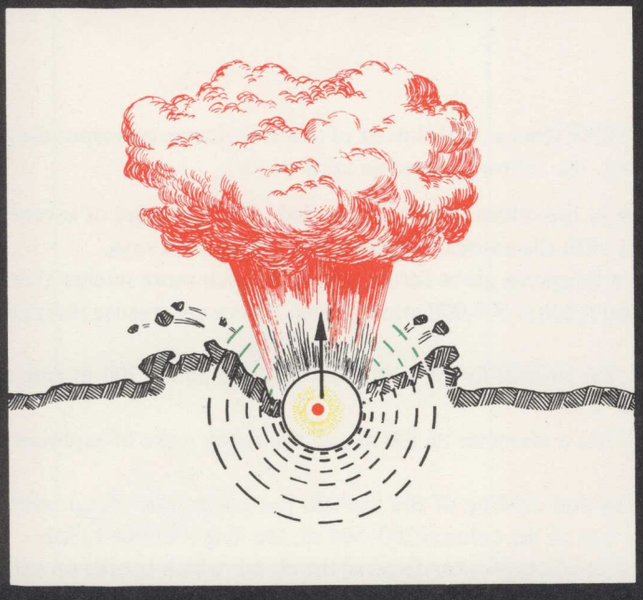
Atomic explosions have primary and secondary effects, thermal, impact and radioactive ones, causing burns, contusions, diseases from radioactivity, destruction and damage to buildings, mechanical constructions, etc. The most terrible consequence is the danger of radioactive contamination.



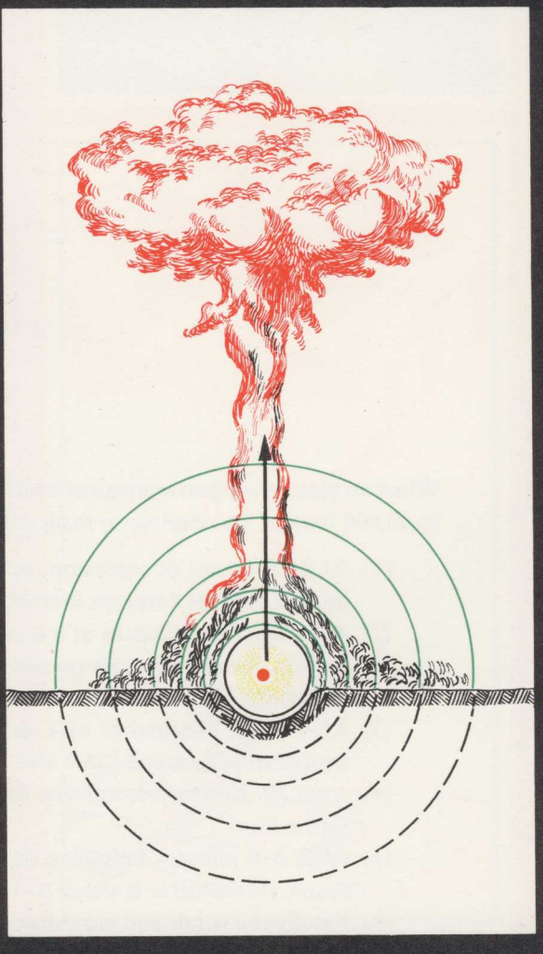
Atomic explosion in the air



Atomic explosion under water



Atomic explosion under ground



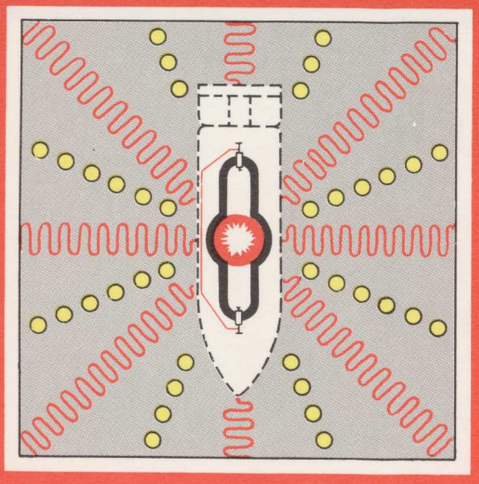
Atomic explosion on the surface

Types of atomic explosion

PROCESS OF DEVELOPMENT IN AN ATOMIC EXPLOSION

When an atomic weapon equivalent to 20 KT/TNT (that is, 20 kilotons of trinitrotoluene, corresponding to 20,000 tons of that explosive) explodes in air, the following process takes place:

(1) At the moment of explosion, as soon as the critical mass has formed, a temperature of several million degrees develops immediately with the emission of neutrons and gamma rays.
(2) After several millionths of a second, a luminous globe forms, which is much more intense than the sun. Surrounding air pressure soon reaches 500,000 atmospheres. There are intense thermal radiations.
(3) After a few hundredths of a second, the fireball forms with a diameter of about 200 m and a temperature between 5,000 and 7,000° C.
(4) After 20–30 or so seconds the fireball has a diameter of 300 m and the shock wave of explosion forms.
(5) After 5–6 minutes following the rising and cooling of the fireball, the mushroom cloud takes shape. Its diameter is about 2–3 km, that of the column 300–500 m, the height about 12 km.
(6) Finally the winds and currents caused by the explosion disperse the cloud, which breaks up and diffuses in the atmosphere.



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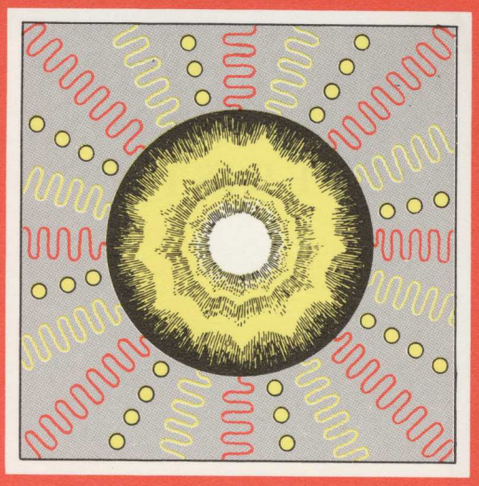

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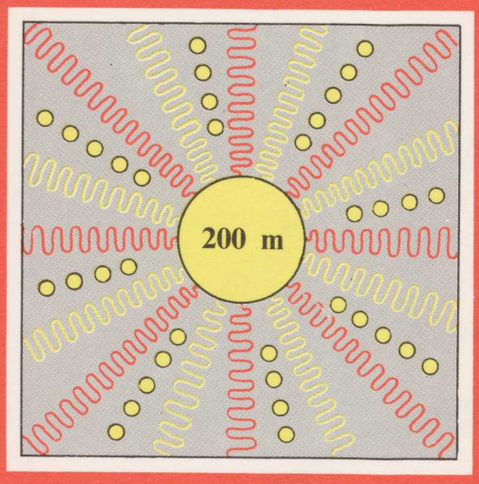

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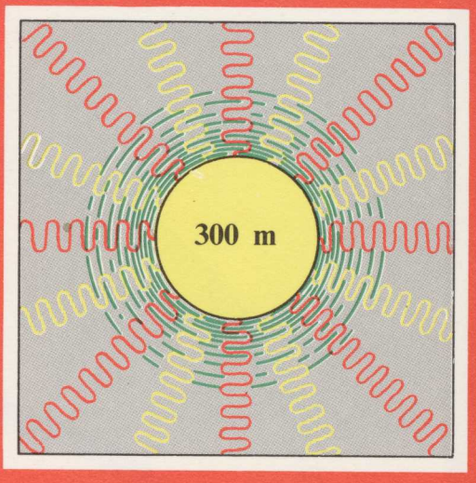

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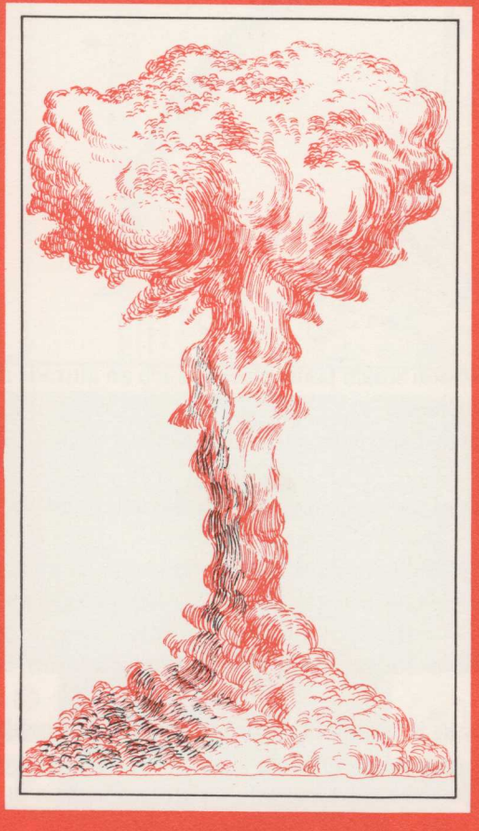


5

6

Neutron radiation

Gamma radiation

Thermal radiation

Shock wave

Process of development in an atomic explosion

OUTWARD APPEARANCE OF AN ATOMIC EXPLOSION IN THE ATMOSPHERE AND ITS PRINCIPAL CHARACTERISTICS

The term 'aerial atomic explosion' means an atomic explosion which takes place at such an altitude that the fireball does not come into contact with the earth's surface.

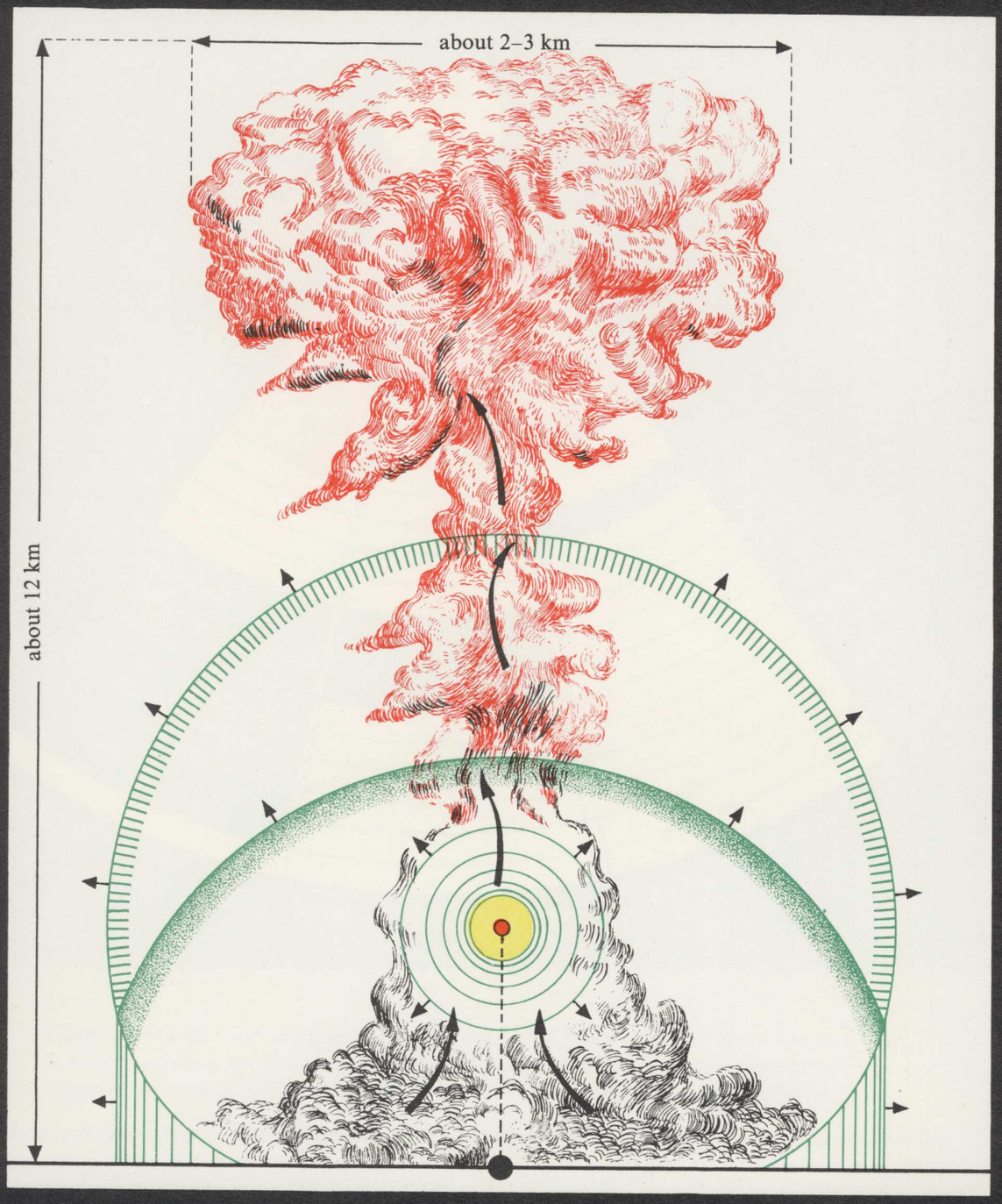
The altitude for an explosion is determined by its power, the conditions of use, method of launching, target, etc.

In the explosion under examination, the three actions of the bomb (shock, thermal and radioactive), take place with great efficacy.

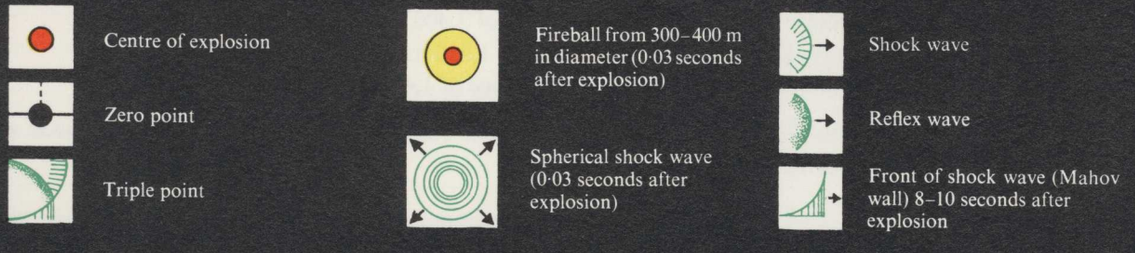
In the first seconds, observed from a distance, the explosion develops apparently in absolute silence, because the explosion is heard slightly later. This explosion is extraordinarily abrupt, resembling thunder, and can be heard at a distance of 20–30 km or more.

First a blinding flash appears, visible at a distance of over 100 km. Soon after, the fireball forms, rises in the air and starts to expand.

A few seconds after the explosion, the fireball cools as it continues to rise, turning into a reddish, mushroom-shaped cloud. Subsequently this cloud turns grey, as in volcanic eruptions. If the explosion has taken place at a limited altitude, a dust cloud forms on the earth's surface, which may remain in the zone for quite a long time.



This is the outward appearance of an atomic explosion, with an explosive power about 20 kilotons/TNT, 5–6 minutes after it has exploded, observed from a distance of 15 km. At the foot of the column there is a dense dust cloud which remains for 10–15 minutes.


Centre of explosion
Zero point
Triple point
Fireball from 300–400 m in diameter (0·03 seconds after explosion)
Spherical shock wave (0·03 seconds after explosion)
Shock wave
Reflex wave
Front of shock wave (Mahov wall) 8–10 seconds after explosion

Outward appearance of an atomic explosion and its principal characteristics

DANGER ZONES FOR SERIOUS, MEDIUM AND MINOR INJURIES

An atomic explosion is characterized by three primary effects (thermal, shock and radioactivity) and by secondary effects. The consequences of each depend on the distance from the centre of the explosion.

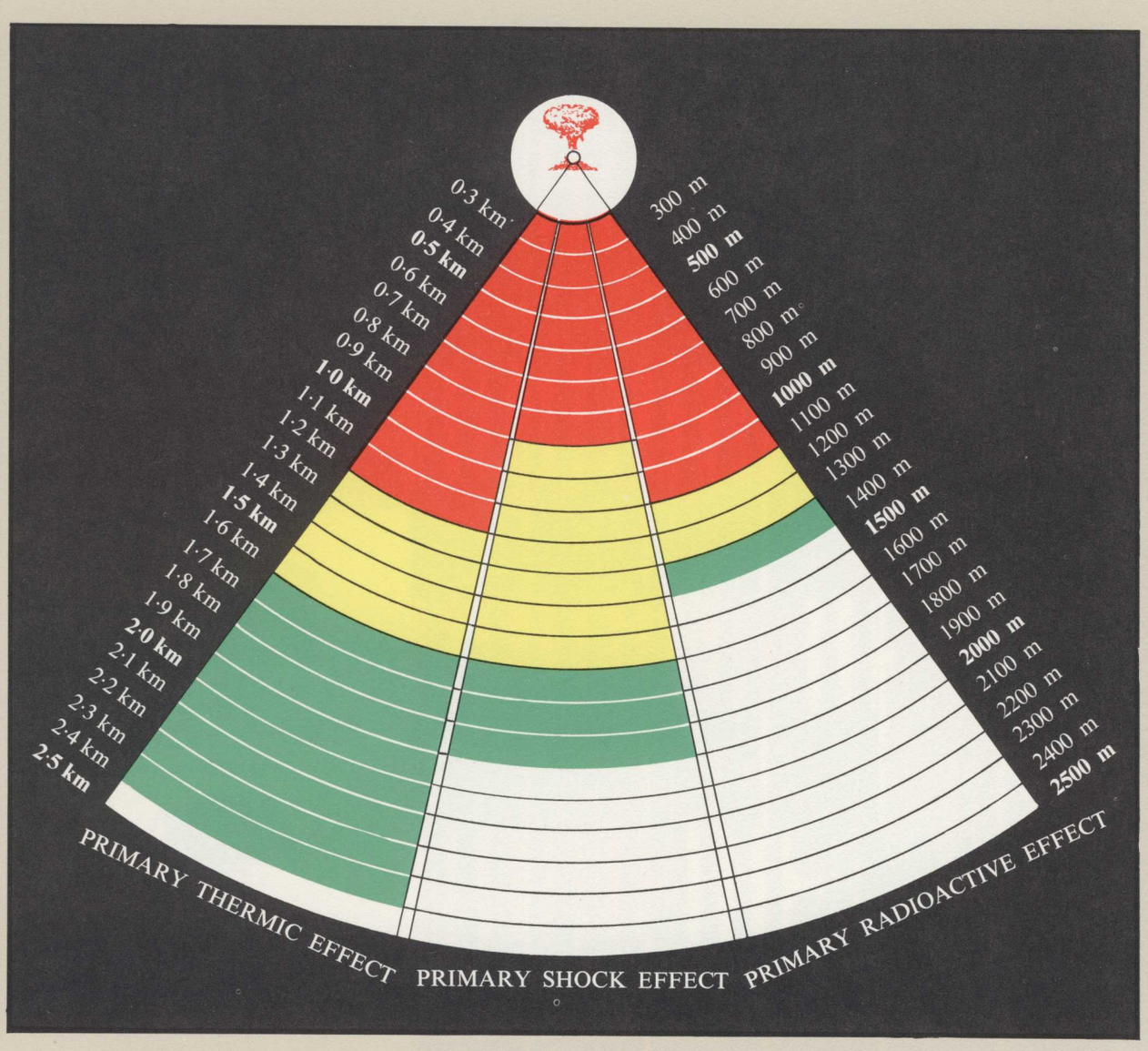
The explosion of an atomic weapon of 20 KT at an altitude of 600 m can affect undefended persons in the following ways:

Serious injuries: from the primary thermal effect at a distance of 1,200 m;
from primary shock effect at a distance of 900 m;
from primary radioactive effect at a distance of 1,100 m.

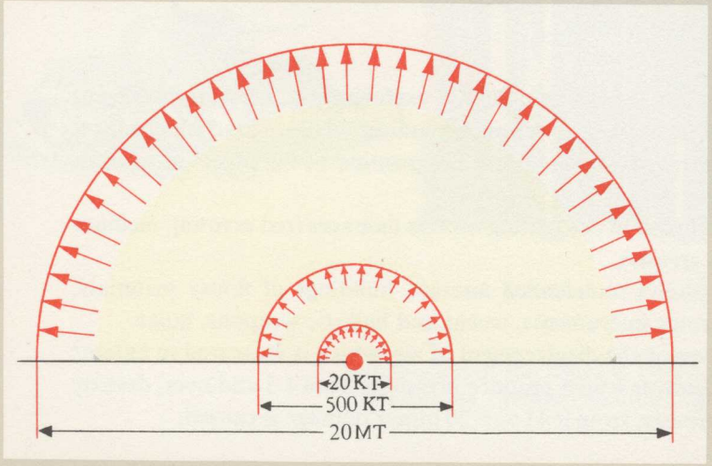
Medium injuries: from primary thermal effect at a distance of 1,800 m;
from primary shock effect at a distance of 1,600 m;
from primary radioactive effect at a distance of 1,300 m.

Minor injuries: primary thermal effect at a distance of 2,400 m;
primary shock effect at a distance of 1,900 m;
primary radioactive effect at a distance of 1,400 m.

Protective measures or immediate counteraction can considerably reduce the thermal, shock and radioactive effects indicated above.



Heat rays, shock effect and radioactivity from a 20 KT bomb at an altitude of 600 m. In the illustration, the distances from the centre at which the human organism suffers injuries are marked (red) serious injuries, (yellow) medium ones, (green) minor ones.



Comparative diameters of the effect of atomic weapons from:
20 KT (20 kiloton)
500 KT (0·5 megaton)
20 MT (20 megaton)

Danger zones for serious, medium and minor injuries

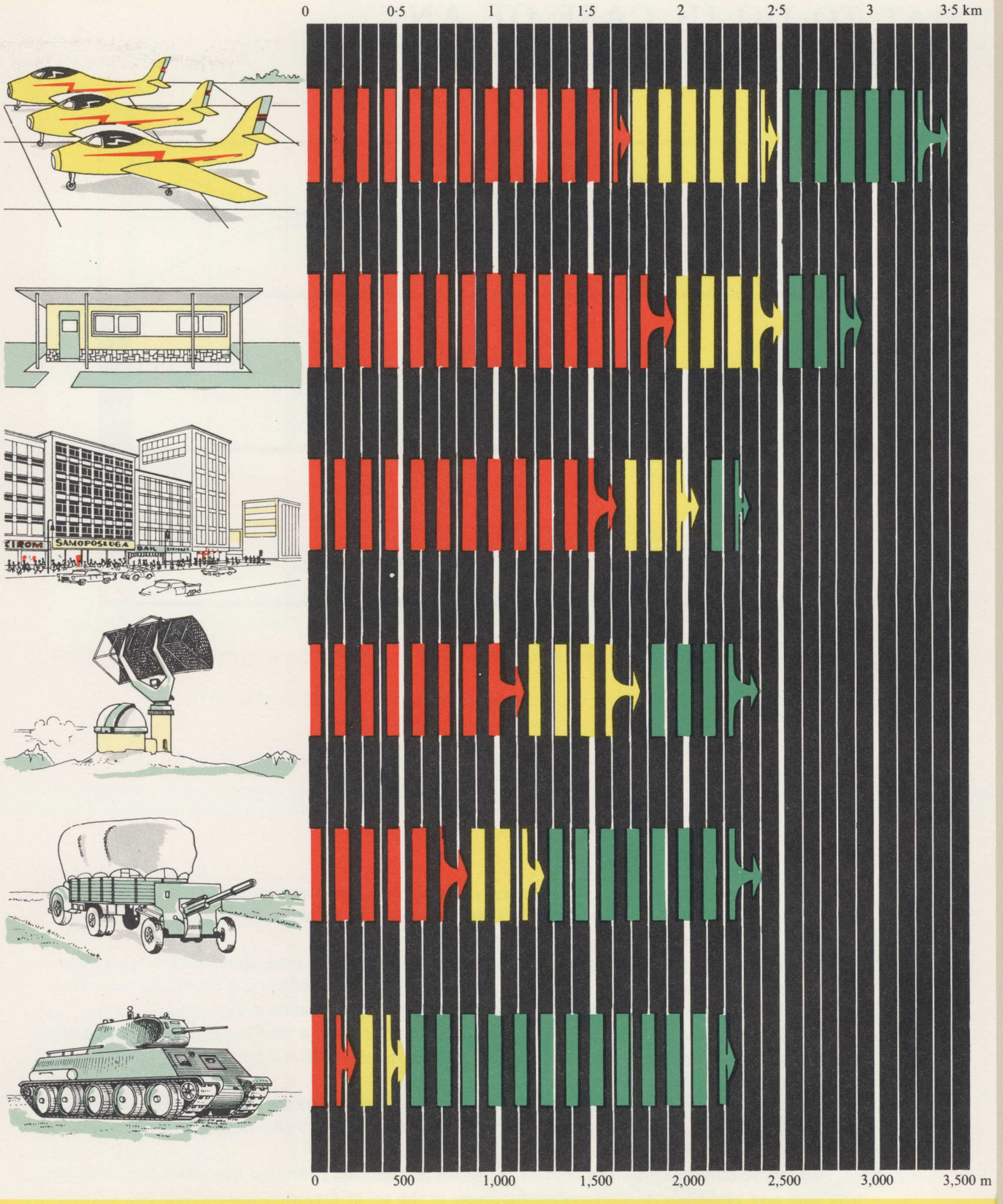
ZONES OF SERIOUS, MEDIUM AND MINOR DAMAGES

The illustration opposite shows the destruction caused by a 20 KT explosion (at a height of 600 m) to various objects. The affected zones and extent of damage are merely indicative, since much depends on the type of explosion, topography and meteorological conditions, the position of the object in relation to the explosion's centre, etc.

These parameters should never be disregarded in calculating serious damages (red arrows), medium ones (yellow arrows) and minor ones (green arrows).

From top to bottom, the illustration shows undefended aircraft, buildings of flimsy materials, buildings of solid materials, radar and electronic instruments, trucks and ballistic weapons, tanks.

The main cause of damage is shock waves or the displacement of air, which is measured in kg/cm^2 or in atmospheres. For example, the displacements which produce pressures from 1·3 and over, destroy buildings, from 1·3 to 0·45 damage them seriously, from 0·45 to 0·20 minor damage is caused.



Subdivision of the zones in which damage to objects occurs:
(red) serious, (yellow) medium, (green) minor.

Zones of serious, medium and minor damages

WHAT TO DO IN CASE OF AN ATOMIC EXPLOSION (in the open)

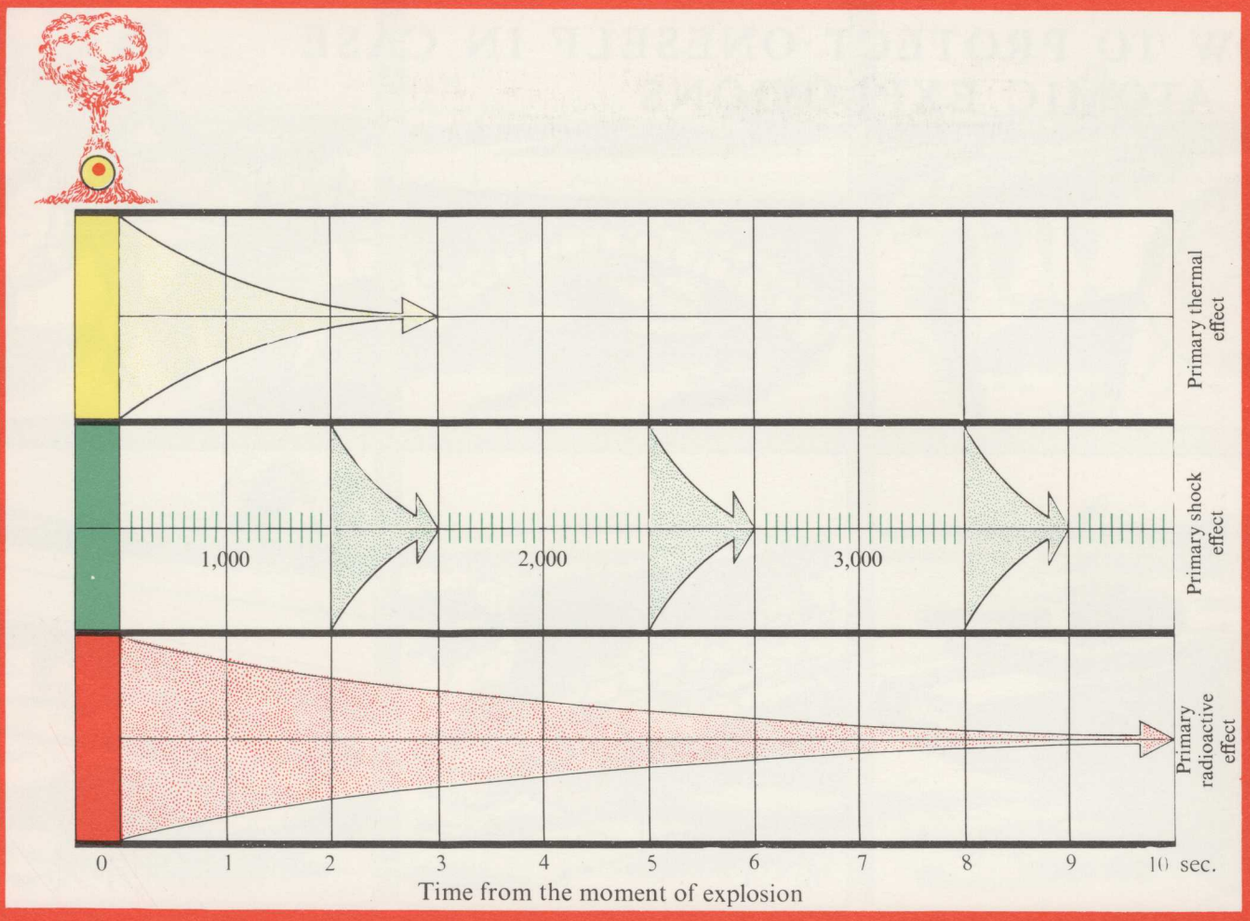
If an atomic explosion occurs it is of the utmost importance to know what steps to take. Knowing the type of explosion, its effects, characteristics and duration of the resulting phenomena, it is possible to protect oneself, provided one remains calm and reacts promptly.

The primary effect (thermal, shock, radioactive) of the explosion is immediate, and if it takes place in the atmosphere, as is probable, it lasts 10 seconds; after about 90 seconds it is practically over. The various primary effects occur simultaneously, while their respective duration differs.

Primary thermal effect: the luminous flash and thermal radiation take place at the moment of explosion; the luminous radiation diffuses in the air at a speed of 300,000 km/sec., while the fireball emits intense radiations for 2–3 seconds.

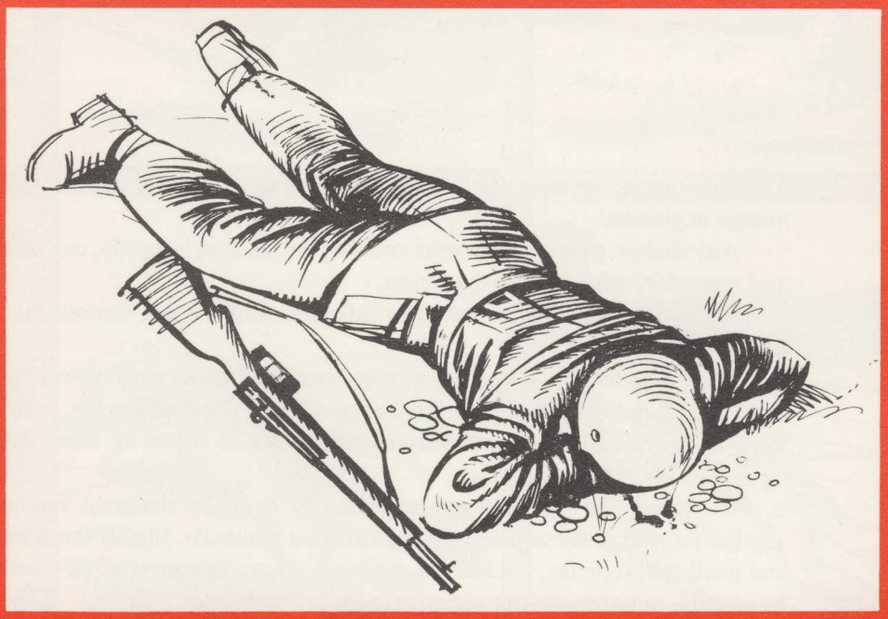
Primary shock effect: the force of the shock wave diminishes as it travels away from the explosion's centre. The shock wave covers the first 1,000 m in 2 seconds, 2,000 m in 5 seconds, 3,000 m in 8 seconds, etc. The passing of the wave front lasts about one second.

Primary radioactive effect: this consists of gamma and neutron radiations (the effect of alpha and beta rays may practically be disregarded); it begins in the act of explosion and lasts several seconds (neutron radiation lasts a fraction of a second). In the first few seconds, 50 per cent of all the radiation is released. Thus at the moment of an atomic explosion there is no sense in running for cover, because every second lost means a greater exposure to the primary effects outlined above. It is worth while aiming for shelter or cover only if it is not more than a step or two away; otherwise one should throw oneself flat on the ground, face downwards, taking up the correct position in relation to the explosion.



The three effects take place almost simultaneously, but their duration differs.

The correct position to adopt in all cases of atomic explosion, especially in the open, is the following: throw oneself flat without hesitation, face downwards, eyes closed, hands hidden beneath the body, legs spread apart in the direction of the explosion.



What to do in case of an atomic explosion (in the open)

HOW TO PROTECT ONESELF IN CASE OF ATOMIC EXPLOSIONS

The illustrations opposite show several ways of using natural or artificial shelter for defence against an atomic explosion.

Any shelter, provided it is near and may be reached instantly, can offer protection from the primary and secondary effects of the explosion.

In the open it is easy to find cover. Mounds, walls, holes, ditches, etc., can be taken advantage of as a protective shield.

Even indoors it is necessary to seek cover which not only affords protection from the immediate thermic and radioactive effects, but above all from the shock wave, which smashes and scatters everything in its path with extraordinary violence, such as windows, tiles, stones, etc., thus causing serious injuries.

Obviously the best cover is afforded by specially designed shelters, equipped with filters and ventilation, and constructed of strong, resistant materials. Ideally these would be provided with sanitary and medicinal supplies; but such shelters will always be scarce, while an atomic explosion could take one by surprise in unforeseeable circumstances.

Some methods of taking cover in case of atomic explosion (the explosion takes place in the top left-hand corner and this enables one to know from which direction the effects can be expected).

ATOMIC WEAPONS

Nuclear weapons, as long-distance weapons, may take the form of bombs transportable to their targets by fighter-bombers, light, medium or heavy bomber aircraft, and the so-called superbombers; they may alternatively be fired from heavy artillery, in which case they will be in the form of missile heads or torpedoes.

As offensive weapons, they may carry radioactive substances, which can be aimed at targets from aircraft, guns or missiles; however, their containers will be constructed in a special way, differing from those for nuclear arms.

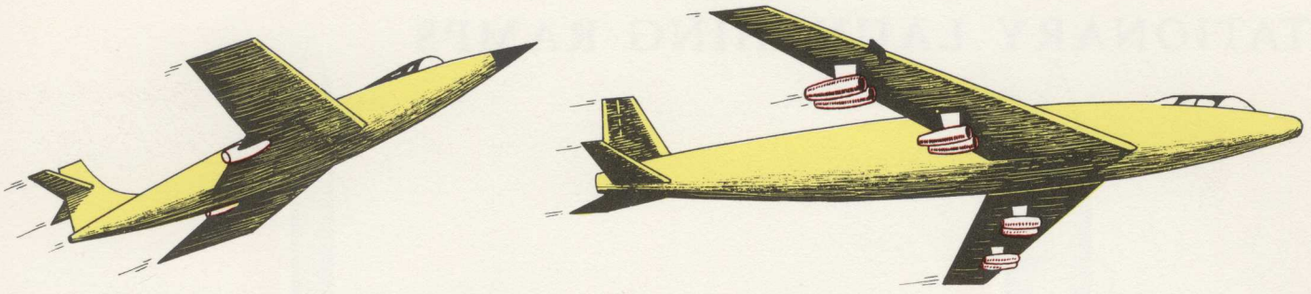
Each type of transportation and launching of nuclear arms has its own characteristics and particular advantages or disadvantages.

Aircraft have a considerable range of action, can fly at great altitudes and speeds, and can operate under almost any weather conditions. Experience acquired in past wars guarantees sufficient precision of aim, even from great altitudes. However, aircraft are easily detectable during flight when nearing the target and can be intercepted by anti-aircraft defence.

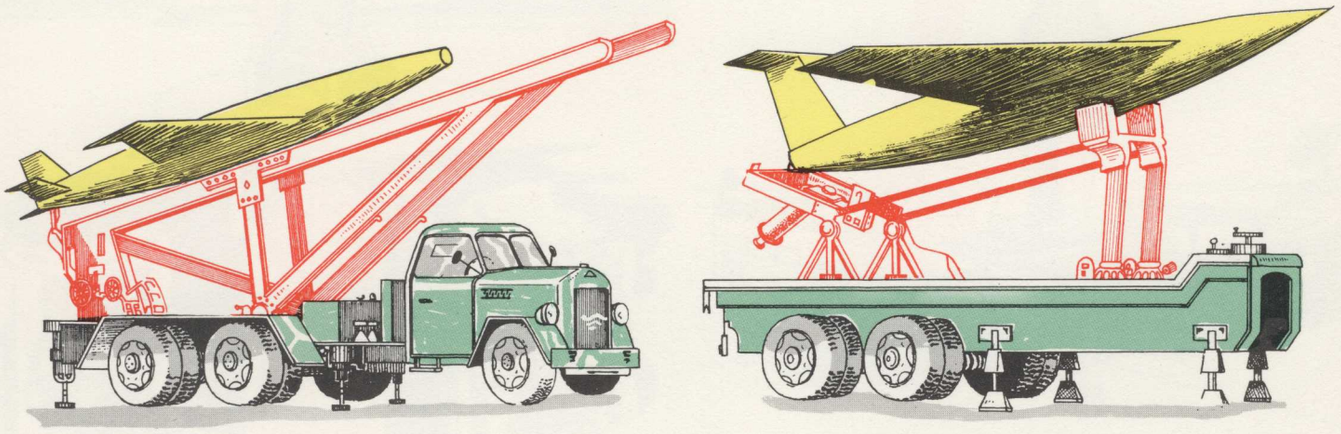
Missiles are harder to intercept because of their enormous speed. Their precision of aim is relatively accurate, but (at least theoretically – there is not enough practical evidence based on experience) it is not only possible to intercept them in flight with anti-missile missiles, but it seems that their navigational system could be influenced by tele-controlled rockets and they could be made to explode in space.

Atomic artillery is perhaps the most accurate offensive weapon, because it can open fire after brief preparation under all conditions, and being mobile, it can easily be concealed from air attack or withdrawn from counterfire. But it can only launch shells of limited effect at reduced distances.

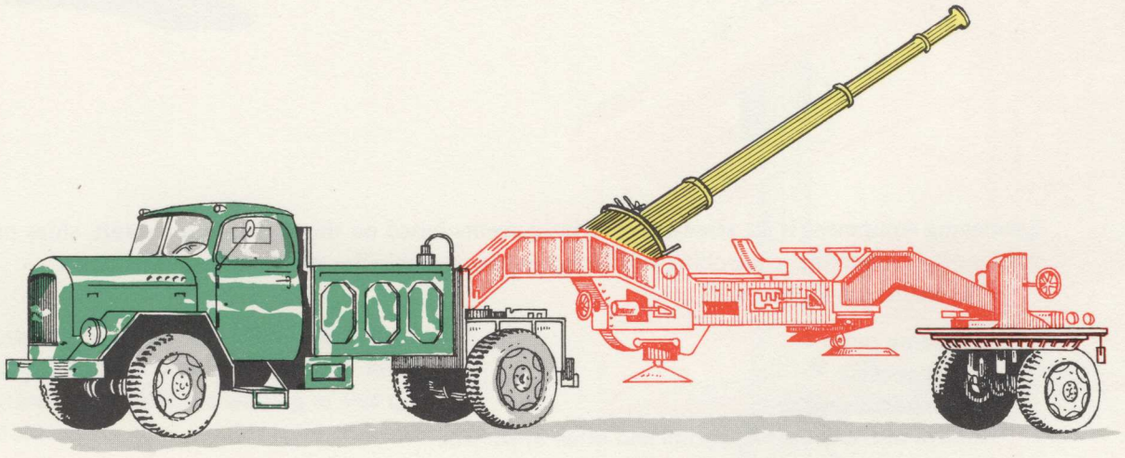
At present, missiles with various range capacities are the principal means of launching atomic weapons.



Fighter-bomber and superbomber



Missiles of different type and range on mobile ramps



Atomic gun or cannon

Atomic arms are put into action with various means of transport and launching

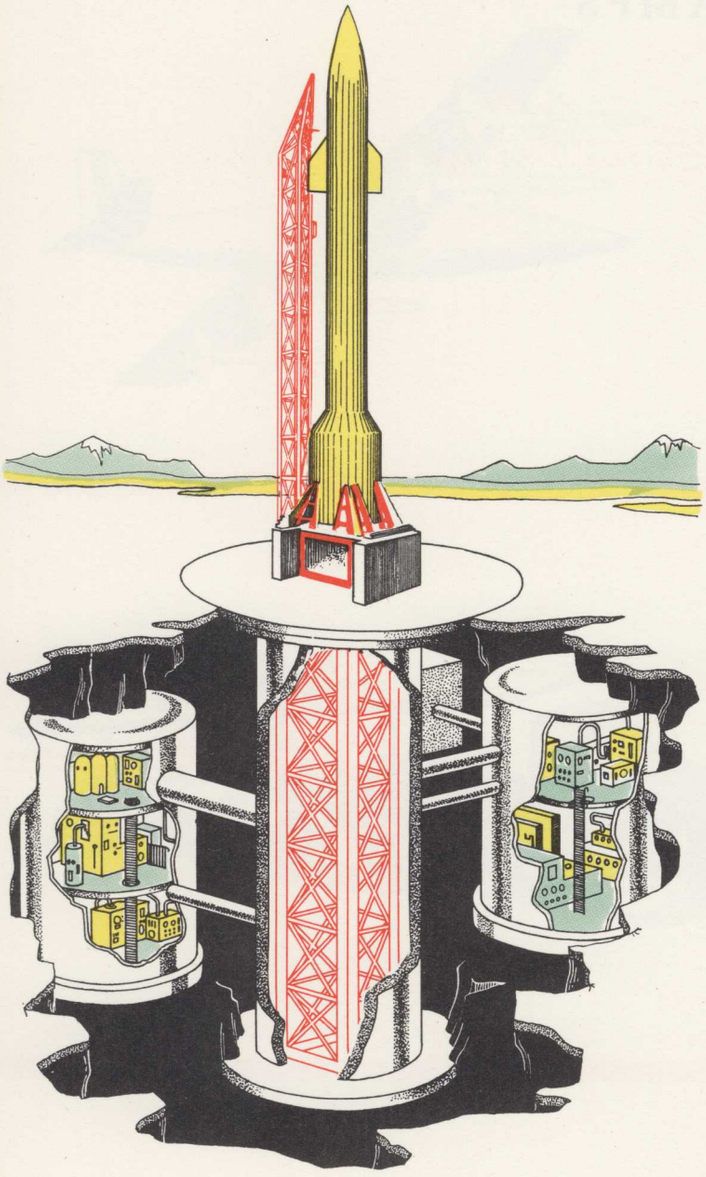
STATIONARY LAUNCHING RAMPS

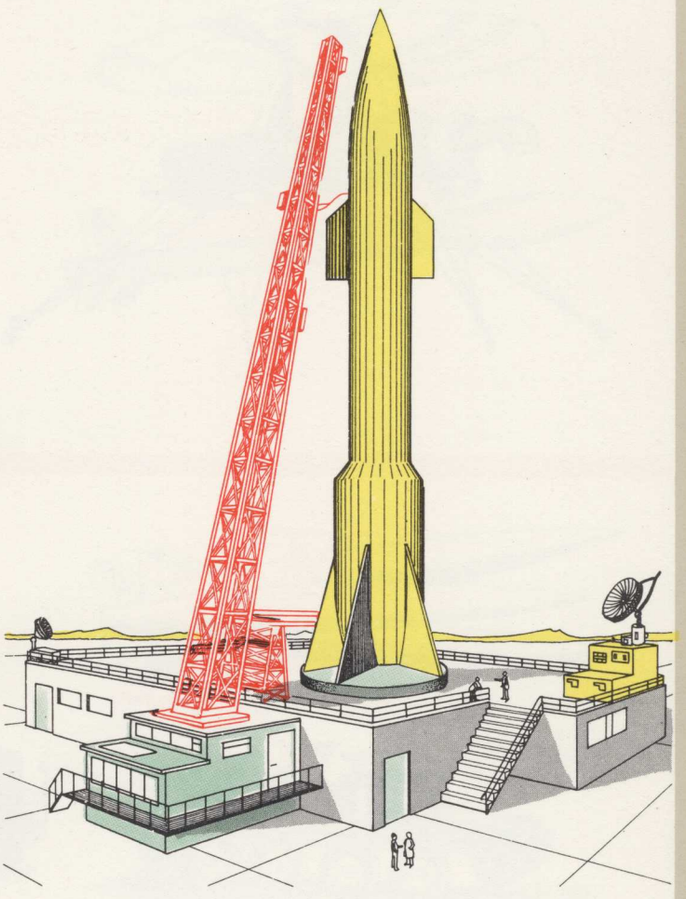
Launching equipment is an assemblage of instruments based on the ground, on aircraft, ships or submarines for conserving, controlling and launching nuclear missiles at a predetermined target.

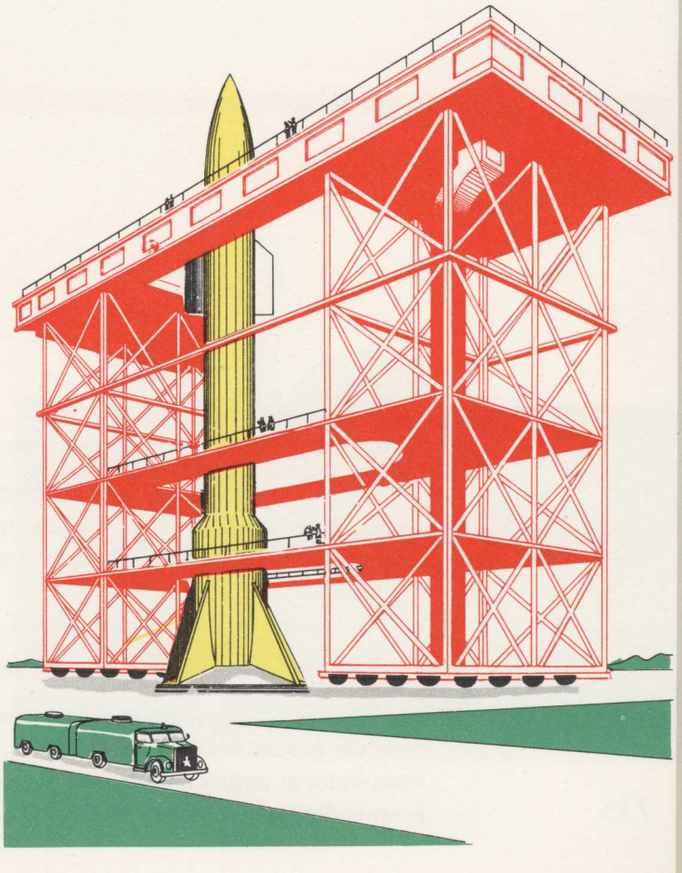
The main components are:

launching ramp
starter rockets
navigational system
control instruments for motors and other apparatus
refuelling systems
assembly and manoeuvre crane
transport means.

The ramps serve for the launching and initial direction-setting of a missile; thus they are of considerable importance. They may differ in form, appearance and size, and can be classified as light, medium and heavy.







Launching ramps are often built on the earth's surface with underground installations. Naturally the shifting of this type of stationary ramp would create problems.

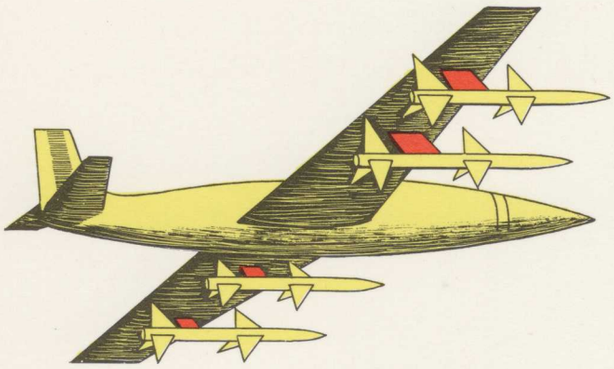
MOBILE LAUNCHING RAMPS

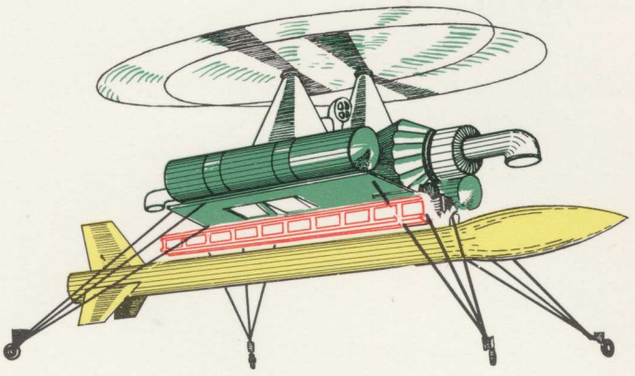
Mobile launching ramps can be installed on:

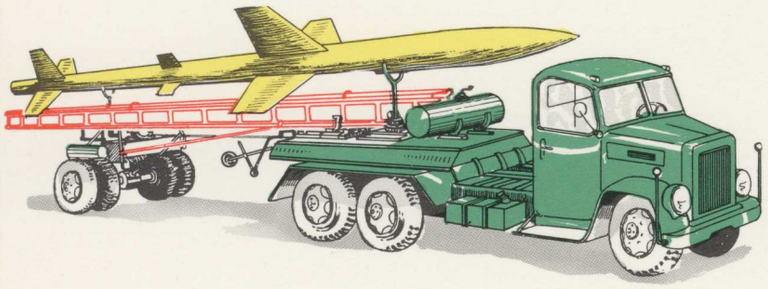
intercepting fighter planes, fighter-bombers, helicopters and other aircraft;
special towing trailers, tanks, adapted trains and other forms of transport;
aircraft-carriers, cruisers, torpedo-boat destroyers and frigates, submarines and submarine platforms;
artificial satellites and other space-craft.

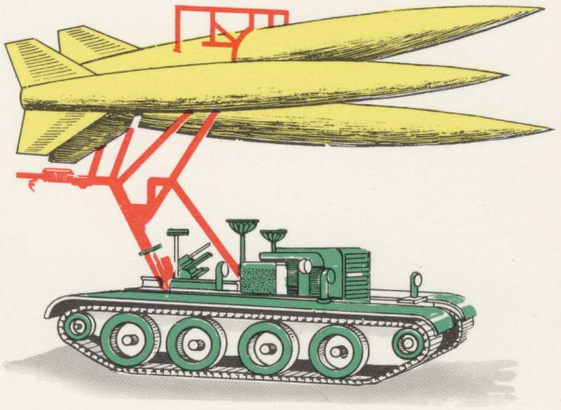
Mobile ramps make these types of launching possible:

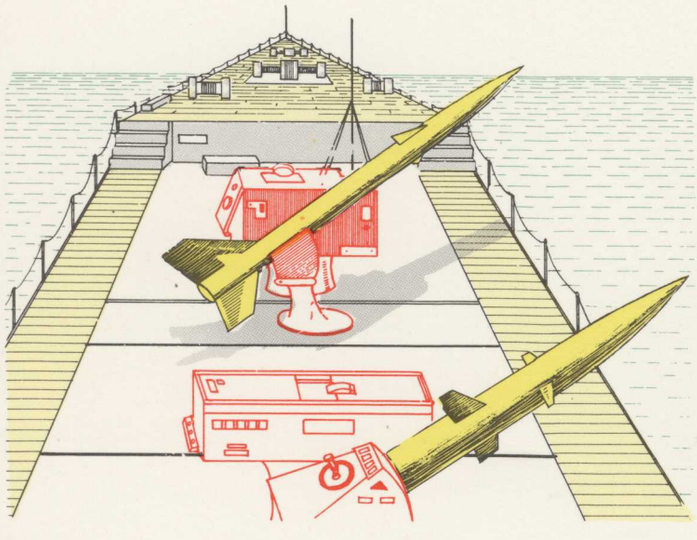
from the air at targets in the air, on land or sea;
from the ground at targets on land, sea, or underwater;
from water at targets on land, sea or in the air;
from underwater at targets on the surface, on land or in the air.

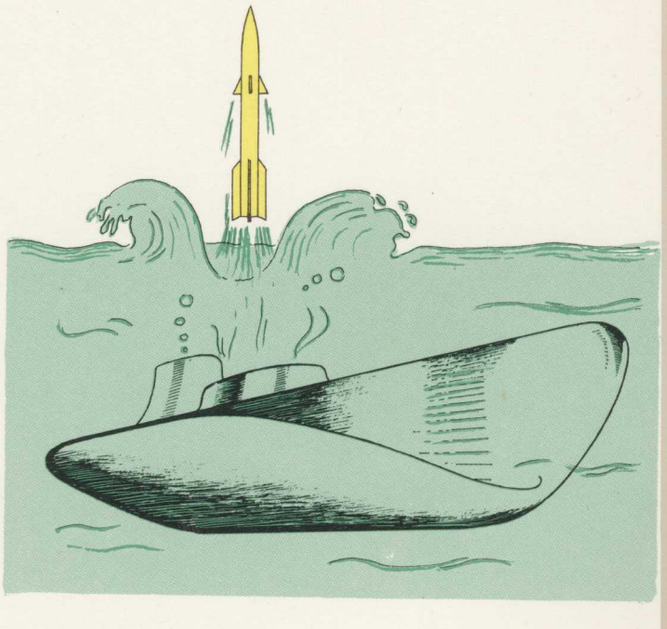












Launching ramps fitted to various means of transport

Mobile launching ramps

TABLES

SYSTEMS OF UNITS OF MEASUREMENT

Physical value	Symbol	UNIT OF MEASUREMENT						Factors for conversion to S.I.	
		S.I.		c.g.s.		Practical system		c.g.s.	Practical system
		Name	Symbol	Name	Symbol	Name	Symbol		
MECHANICAL VALUES									
Length	l	metre	m	centimetre	cm	metre	m	10^{-2}	1
Time	t	second	s (sec)	second	s (sec)	second	s (sec)	1	1
Mass	m	kilogram	kg	gram	g	kilogram weight sec^2/metre	kg m^{-1} · sec^2	10^{-3}	9·80
						atom mass unit	amu		$1{\cdot}6598 \times 10^{-27}$
Plane angle	a	radian	rad	radian	rad	radian	rad		1
						degree	°	1	0·0174533
Solid angle	ω, Ω	steradian	ster	steradian	ster	steradian	ster	1	1
Surface	S	metre^2	m^2	centimetre^2	cm^2	metre^2	m^2	10^{-4}	1
Volume	V	metre^3	m^3	centimetre^3	cm^3	metre^3	m^3	10^{-6}	1
						litre	l		$1{\cdot}000027 \times 10^{-3}$
Volume capacity	Q	metre^3/sec	m^3 · s^{-1}	centimetre^3/sec	cm^3 · s^{-1}	metres^3/sec	m^3 · s^{-1}	10^{-6}	1
						litres/sec	l · s^{-1}		$1{\cdot}000027 \times 10^{-3}$
Linear velocity	v	metre/second	m · s^{-1}	centimetre/sec	cm · s^{-1}	metre/sec	m · s^{-1}	10^{-2}	1
						kilometre/hour	km · h^{-1}		−1/3,6
						mach	M		331·45
Angular velocity	ω	radian/sec	rad · s^{-1}	radian/sec	rad · s^{-1}	radian/sec	rad · s^{-1}	1	1
						revs/minute	rpm		$120 \times \pi$
Period	τ	second	s	second	s	second	s	1	1

Frequency	v, f	hertz (cycle/sec)	Hz	hertz (cycle/sec)	Hz	hertz (cycle/sec) revs/minute	Hz rpm	1	1 $120 \times \pi$
Pulsation	ω	hertz (radian/sec)	Hz	hertz (radian/sec)	Hz	hertz revs/minute	Hz rpm	1	1 $120 \times \pi$
Linear acceleration	a	metre/sec^2	$m \cdot s^{-2}$	centimetre/sec^2	$cm \cdot s^{-2}$ (gal)	metre/sec^2	$m \cdot s^{-2}$	10^{-2}	1
Angular acceleration	γ	radian/sec^2	$rad \cdot s^{-2}$	radian/sec^2	$rad \cdot s^{-2}$	radian/sec^2	$rad \cdot s^{-2}$	1	1
Force	F	Newton	N	dyne	dyn	kilogram-weight	kg	10^{-5}	9·80
Specific mass	ρ, δ	bessel/metre^3	$Bes \cdot m^{-3}$	gram/cm^3	$g \cdot cm^{-3}$				
Specific weight	P	Newton/metre^3	$N \cdot m^{-3}$	dyne/cm^3	$dyn \cdot cm^{-3}$	kilogram-weight/metre^3	$kg \cdot m^{-3}$	10	9·80
Moment of inertia	I	bessel · metre^2	$Bes \cdot m^2$	gram · cm^2	$g \cdot cm^2$	kilogram-weight · metre · sec^2	$kg \cdot m \cdot s^2$	10^{-7}	9·80
Moment of force	M	Newton · metre	$N \cdot m$	dyne · centimetre	dyn · cm	kilogram-weight · metre	$kg \cdot m$	10^{-7}	9·80
Quantity of movement	q	bessel · metre/sec	$Bes \cdot m \cdot s^{-1}$	gram · centimetre/sec	$g \cdot cm \cdot s^{-1}$	kilogram-weight · sec	$kg \cdot s$	10^{-5}	9·80
Moment of quantity of movement	m	bessel · metre^2/sec	$Bes \cdot m^2 \cdot s^{-1}$	gram · centimetre^2/sec	$g \cdot cm^2 \cdot s^{-1}$	kilogram-weight · metre/sec	$kg \cdot m \cdot s^{-1}$	10^{-7}	9·80
Impulse	J	Newton · second	$N \cdot s$	dyne · second	dyn · s	kilogram-weight · sec	$kg \cdot s$	10^{-5}	9·80
Moment of impulse	m	Newton · sec · metre	$N \cdot s \cdot m$	dyne · sec · centimetre	dyn · s · cm	kilogram-weight · metre · sec	$kg \cdot m \cdot s$	10^{-7}	9·80
Work, energy	L, E, T, V, W	joule	J	erg	erg	kilogram-weight · metre calorie kilowatt hour litre-atmosphere electronvolt	$kg \cdot m$ cal kWh $1 \cdot atm.$ eV	10^{-7}	9·80 4·186 $3{\cdot}6 \times 10^6$ 101·33 $1{\cdot}60206 \times 10^{-19}$
Power	W	watt	W	erg/second	$erg \cdot s^{-1}$	kilogram-weight · metre/sec calorie/sec horse power	$kg \cdot m \cdot s^{-1}$ $cal \cdot s^{-1}$ h.p.	10^{-7}	9·80 4·186 745·2
Pressure	p	Newton/metre^2	$N \cdot m^{-2}$	dynes/cm^2 (microbar)	$dyn \cdot cm^{-2}$	kilogram-weight/metre^2 kilogram-weight/cm^2 atmosphere millimetre of mercury centimetre of H_2O	$kg \cdot m^{-2}$ $kg \cdot cm^{-2}$ atm. mm-Hg cm-H_2O	10^{-1}	9·80 $9{\cdot}80 \times 10^4$ $1{\cdot}012 \times 10^5$ (3) 133·2 (3) 98·0
Coefficient of viscosity	η	bessel · /metre · sec	$Bes \cdot m^{-1} s^{-1}$	dynes · s/cm^2 (poise)	P	kilogram-weight · sec/metre^2	$kg \cdot s \cdot m^{-2}$	10^{-1}	9·80
Surface tension	τ	Newton/m, joule/m^2	$N \cdot m^{-1}$, $J \cdot m^{-2}$	dynes/cm, $erg \cdot cm^{-2}$	$dyn \cdot cm^{-1}$, $erg \cdot cm^{-2}$	kilogram-weight/metre	$kg \cdot m^{-1}$	10^{-3}	9·80

Physical value	Symbol	UNIT OF MEASUREMENT						Factors for conversion to S.I.	
		S.I.		c.g.s.		Practical system		c.g.s.	Practical system
		Name	Symbol	Name	Symbol	Name	Symbol		
THERMAL VALUES									
Temperature	t, T	degree Celsius	°C	degree Celsius	°C	degree Celsius degree Kelvin	°C °K	1	1 1
Quantity of heat	Q	joule	J	erg	erg	calorie kilocalorie	cal kcal	10^{-7}	4·186 4·186
Thermal capacity	C	joule/°C	$J \cdot °C^{-1}$	erg/°C	$erg \cdot °C^{-1}$	calorie/°C	$cal \cdot °C^{-1}$	10^{-7}	4·186
Specific heat	C	joule/bessel °C	$J \cdot Bes^{-1}\ °C^{-1}$	$erg/g \cdot °C$	$erg/g^{-1} \cdot °C^{-1}$				4·186
Entropy	S	joule/°C	$J \cdot °C^{-1}$	erg/°C	$erg \cdot °C^{-1}$	cal/°C	$cal \cdot °C^{-1}$	10^{-7}	4·186
PHOTOMETRIC VALUES									
Luminous energy	W	joule	J	erg	erg			10^{-7}	
Luminous flux	Φ	watt	W	erg/second	$erg \cdot s^{-1}$	lumen	lumen	10^{-7}	0·001496 (5)
Luminous intensity or intensity of emission	I	watt/steradian	$W \cdot ster^{-1}$	erg/sec · steradian	$erg \cdot s^{-1} \cdot ster^{-1}$	candle	candle	10^{-7}	
Intensity of illumination	E	watt/metre^2	$W \cdot m^{-2}$	erg/sec · cm^2	$erg \cdot s^{-1} \cdot cm^{-2}$	lumen/m^2 lumen/cm^2	lux phot	 10^{-3}	
Surface brightness (luminance)	Σ	watt/m^2 · steradian	$W \cdot m^{-2} \cdot ster^{-1}$	erg/sec · cm^2 · steradian	$erg \cdot s^{-1} \cdot cm^{-2} \cdot ster^{-1}$	candle/m^2 candle/cm^2	 .sb	 10^{-3}	
ACCOUSTIC VALUES									
Sound energy	W	joule	J	erg	erg	erg		10^{-7}	
Sound output/power	Φ	watt	W	erg/second	$erg \cdot s^{-1}$	$erg \cdot s^{-1}$		10^{-7}	
Sound intensity	E	watt/metre^2	$W \cdot m^{-2}$	erg/sec · cm^2	$erg \cdot s^{-1} \cdot cm^{-2}$			10^{-3}	
Loudness	η					phon	phon		

ELECTRIC AND MAGNETIC VALUES						The units of measurement, symbols and dimensions of electrical values in the electrotechnical system are the same as for the S.I. system, in both name and symbol columns.	The units of measurement, symbols and dimensions of electrical values in the electrotechnical system are the same as for the S.I. system, in both name and symbol columns.		
Electrical charge	Q, q	coulomb	C	franklin				$10^{-9}/2{\cdot}9979$	1
Electric moment	m	coulomb · metre	C · m	e.s.u.				$10^{-11}/2{\cdot}9979$	1
Dielectric constant	ε	farad/metre	$F \cdot m^{-1}$	e.s.u.				$8{\cdot}854 \times 10^{-12} (= \varepsilon_0)$	1
Relative dielectric constant	ε_r							1	1
Electric field strength	F	volt/metre	$V \cdot m^{-1}$	e.s.u.				$2{\cdot}9979 \times 10^4$	1
Electric induction	D	coulomb/metre^2	$C \cdot m^{-2}$	e.s.u.				$10^{-5}/2{,}9979$	1
Electric induction flow	$\Phi(D)$	coulomb	C	e.s.u.				$10^{-9}/2{,}9979$	1
Difference of potential	V, f	volt	V	e.s.u.				$2{,}9979 \times 10^2$	1
Surface electrical density	σ	coulomb/metre^2	$C \cdot m^{-2}$	e.s.u.				$10^{-5}/2{\cdot}9979$	1
Density of spatial charge or volume	ρ	coulomb/metre^3	$C \cdot m^{-3}$	e.s.u.				$10^{-3}/2{\cdot}9979$	1
Capacity	C	farad	F	centimetre	cm			$10^{-11}/8{\cdot}9876$	1
Current strength	i	ampere	A	e.s.u.				$10^{-9}2{\cdot}9979$	1
Resistance	R	ohm	Ω	e.s.u.				$8{\cdot}9876 \times 10^{11}$	1
Specific resistance	ρ	ohm · metre	$\Omega \cdot m$	e.s.u.				$8{\cdot}9876 \times 10^9$	1
Conductivity	σ	siemens, mho	mho	e.s.u.				$10^{-11}/8{\cdot}9876$	1
Specific conductivity	χ	siemens/metre	$mho \cdot m^{-1}$	e.s.u.				$10^{-9}/8{\cdot}9876$	1
Magnetic induction	B	tesla, weber/metre^2	T, $Wb\ m^{-2}$	e.s.u.				$2{\cdot}9979 \times 10^6$	1
Magnetic permeability	μ	henry/metre	$H \cdot m^{-1}$	e.s.u.				$11{\cdot}3 \times 10^{14}$	1
Relative magnetic permeability	μ_r							1	1
Magnetic field strength	H	ampere/metre	$A \cdot m^{-1}$	e.s.u.				$10^{-7}/(4 \times \pi \times 2{\cdot}9979)$	1
Magnetic induction flux	$\Phi(B)$	weber	Wb	e.s.u.				$2{\cdot}9979 \times 10^2$	1
Magnetic moment	m	weber · metre	Wb · m	e.s.u.				$4\pi \times 2{\cdot}9979$	1
Coefficient of selfinduction	L	henry	H	e.s.u.				$8{\cdot}9876 \times 10^{11}$	1

NUMERICAL VALUES OF

1 metre = 1,650,763·73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2_{p_{10}}$ and 5_{d_5} of the krypton – 86 atom.

1 kilogram = mass of the international kilogram kept at Sèvres.

1 second = 9,192,631,770 periods of the radiation corresponding to the transition between the two hyper-refined levels of the ground state of the cesium – 133 atom.

1 Kelvin = defined on the basis of the thermodynamic scale of temperatures, assigning the temperature 273·16 °K to the triple point of natural water. (On the Celsius scale: absolute zero = −273·15 °C, triple point = + 0·01 °C.)

Normal gravitational acceleration = 9·806 65 m s^{-2}

Normal atmosphere = 1013,250 dyn cm^{-2}.

1 inch = 2·54 cm.

1 pound (avdp.) = 0·45359237 kg.

1 Angstrom (Å) = 10^{-10} metre. → 1 thermochemical calorie = cal_{th} = 4·184 × 10^7 erg.

1 calorie IT = cal_{IT} = 4·1868 × 10^7 erg.

1 litre = 1,000·028 cm^3.

1 mole/mass = number of atoms contained in 12 g of the pure isotope ^{12}C.

Basis of the unified scale of atomic weights, $^{12}C \equiv 12$.

Ratio between the basis of the physical scale ($^{16}0 \equiv 16$) and the basis of the unified scale, 1·00317917 ± 0·000000051.

Ratio between the basis of the chemical scale ($0 \equiv 16$) and the basis of the unified scale, 1·000043 ± 0·000015.

Avogrado's constant, $N = (6{,}022{\cdot}52 \pm 0{\cdot}27) \times 10^{20}$ (g mol)$^{-1}$.

Normal volume of an ideal gas, $V_0 = (22{,}413{\cdot}6 \pm 3{\cdot}0)$ cm^3 (g mol)$^{-1}$.

Loschmidt's constant, $L_0 = N/V_0 = (2{,}687{\cdot}0 \pm 0{\cdot}3) \times 10^{16}$ cm^{-3}.

Constant of an ideal gas, or gases, $R_0 = (82{\cdot}055 \pm 0{\cdot}011)$ cm^3 atm (g mol °K)$^{-1}$,

$= (8{\cdot}31434 \pm 0{\cdot}00105)$ joule (g mol °K)$^{-1}$.

Boltzmann's constant, $k = R_0/N = (13{,}805{\cdot}4 \pm 1{\cdot}8) \times 10^{-20}$ erg °K^{-1}.

Mass of hydrogen atom, $m'_H \equiv 1{\cdot}0078252 \pm 0{\cdot}0000002$.

Mass of proton, $m'_p \equiv 1{\cdot}00727663 \pm 0{\cdot}00000024$.

Mass of neutron, $m'_n \equiv 1{\cdot}0086654 \pm 0{\cdot}0000012$.

Mass of electron, $m'_e \equiv (5{\cdot}48597 \pm 0{\cdot}00009) \times 10^{-4}$.

Rest mass of electron, $m_e = (9{,}109{\cdot}08 \pm 0{\cdot}39) \times 10^{-31}$ g.

Ratio between the mass of the proton and the mass of the electron, $m_p/m_e = 1{,}836{\cdot}10 \pm 0{\cdot}03$.

Speed of light in space, $c = (299{,}792{\cdot}5 \pm 0{\cdot}3)$ km s^{-1}.

Faraday's constant, $F = Ne = (28{,}926{\cdot}1 \pm 0{\cdot}6) \times 10^{10}$ esu (g mol)$^{-1}$,

$F' = (96{,}487{\cdot}0 \pm 1{\cdot}5)$ coulomb (g mol)$^{-1}$.

Electron charge, $e = (48{,}029{\cdot}8 \pm 2{\cdot}1) \times 10^{-14}$ esu,

$e' = (16{,}021{\cdot}0 \pm 0{\cdot}6) \times 10^{-24}$ emu.

Ratio between the charge and mass of the electron $e/m_e = (52{,}727{\cdot}4 \pm 0{\cdot}6) \times 10^{13}$ esu g^{-1},

$e'/m_e = (17{,}587{,}960 \pm 180)$ emu g^{-1}.

Classical radius of the electron, $r_e = e^2/m_e c^2 = (28{,}177{\cdot}7 \pm 1{\cdot}2) \times 10^{-17}$ cm.

Thomson collison cross-section, $\sigma_T = 8\pi r_e^2/3 = (6{\cdot}6516 \pm 0{\cdot}0006) \times 10^{-25}$ cm^2.

Plank's constant, $h = (6{,}625{\cdot}59 \pm 0{\cdot}48) \times 10^{-30}$ erg s.

Plank's reduced constant, $h = h/2\pi = (10{,}544{\cdot}94 \pm 0{\cdot}75) \times 10^{-31}$ erg s.

BASIC PHYSICAL CONSTANTS

Rydberg's constant in wave number for infinite nuclear mass,
$$R\infty = \alpha^2 mc/2h = (109{,}737{\cdot}31 \pm 0{\cdot}03)\ \mathrm{cm}^{-1}.$$
Rydberg's constant in frequency for infinite nuclear mass,
$$R'_\infty = R\infty\, c = (328{,}984{\cdot}2 \pm 0{\cdot}6) \times 10^{10}\ \mathrm{s}^{-1}.$$
Rydberg's constant in energy for infinite nuclear mass,
$$R''_\infty = R\infty\, hc = (21{,}797{\cdot}1 \pm 1{\cdot}5) \times 10^{-15}\ \mathrm{erg}.$$
Rydberg's constant in wave number for light hydrogen, $R_{1H} = (109{,}677{\cdot}58 \pm 0{\cdot}03)\ \mathrm{cm}^{-1}$.
Bohr's radius of the first atom orbit for an infinite nuclear mass,
$$a\infty = h^2/me^2 = (52{,}916{\cdot}7 \pm 0{\cdot}6) + 10^{-13}\ \mathrm{cm}.$$
Bohr's radius for the first atom orbit for ^{1}H, referred to the centre of mass,
$$a = (52{,}916{\cdot}7 \pm 0{\cdot}6) \times 10^{-13}\ \mathrm{cm}.$$
Constant of refined structure, $\alpha = 2\pi e^2/hc = 1/(137{\cdot}0388 \pm 0{\cdot}0018)$.
Zeeman's division for gauss, $e/4\pi mc^2 = (4{\cdot}66858 \pm 0{\cdot}00004) \times 10^{-5}\ \mathrm{cm}^{-1}\ \mathrm{G}$.
Bohr's magneton, $\mu_B = \hbar e/2m_e c = (9{,}273{\cdot}2 \pm 0{\cdot}6) \times 10^{-24}\ \mathrm{erg\ G}^{-1}$.
Magnetic moment of the electron, $\mu_2 = (9{,}283{\cdot}9 \pm 0{\cdot}6) \times 10^{-24}\ \mathrm{erg\ G}^{-1}$.
Magnetic moment of the proton, $\mu_p = (14{,}104{\cdot}9 \pm 1{\cdot}2) \times 10^{-27}\ \mathrm{erg\ G}^{-1}$.
Magnetic moment of the proton (bare), $\mu_p/\mu_n = 2{\cdot}79276 \pm 0{\cdot}00006$.
Magnetic moment of the proton (spherical sample of H_2O), $\mu'_p/\mu_n = 2{\cdot}79268 \pm 0{\cdot}00006$.
Nuclear magneton, $\mu_N = \hbar eN/2m_p c^2 = (5{,}050{\cdot}50 \pm 0{\cdot}39) \times 10^{-27}\ \mathrm{erg\ G}^{-1}$.
Gyromagnetic frequency of the proton, $\gamma = (26{,}751{\cdot}92 \pm 0{\cdot}21)\ \mathrm{s}^{-1}\ \mathrm{G}^{-1}$,
$\gamma/2\pi = (4{,}257{\cdot}70 \pm 0{\cdot}03)\ \mathrm{s}^{-1}\ \mathrm{G}^{-1}$.

Compton's wavelength:

for the electron, $\lambda c_e = (24{,}262{\cdot}1 \pm 0{\cdot}6) \times 10^{-14}\ \mathrm{cm}$,
for the proton, $\lambda c_p = (13{,}213{\cdot}98 \pm 0{\cdot}39) \times 10^{-17}\ \mathrm{cm}$,
for the neutron $\lambda c_n = (13{,}195{\cdot}9 \pm 0{\cdot}4) \times 10^{-17}\ \mathrm{cm}$.

Stefan-Boltzmann's constant, $\sigma = (\pi^2/60)(k^4/\hbar^3 c^2) = (5{,}669{\cdot}7 \pm 3{\cdot}0) \times 10^{-8}\ \mathrm{erg\ cm}^{-2}\ \mathrm{s}^{-1}\ ^\circ\mathrm{K}^{-4}$.
1st constant of radiation, $c_1 = 2\pi hc^2 = (3{,}741{\cdot}50 \pm 0{\cdot}27) \times 10^{-8}\ \mathrm{erg\ cm}^2\ \mathrm{s}^{-1}$.
2nd constant of radiation, $c_2 = hc/k = (1{\cdot}43879 \pm 0{\cdot}00018)\ \mathrm{cm}\ ^\circ\mathrm{K}$.
Constant of specific atomic heat, $c_2/c = (4{\cdot}7993 \pm 0{\cdot}0006) \times 10^{-11}\ \mathrm{s}\ ^\circ\mathrm{K}$.
Wien's constant (displacement law), $c^2/4{\cdot}965114 = (0{\cdot}28978 \pm 0{\cdot}00004)\ \mathrm{cm}\ ^\circ\mathrm{K}$.

Conversion factors mass-energy:

$$1\mathrm{g} \equiv (56{,}098{\cdot}5 \pm 0{\cdot}8) \times 10^{22}\mathrm{MeV},$$
Mass of the electron $\equiv (511{\cdot}006 \pm 6)$ MeV,
Mass of the proton $\equiv (938{\cdot}256 \pm 0{\cdot}015)$ MeV,
Mass of the neutron $\equiv (939{\cdot}550 \pm 0{\cdot}015)$ MeV,
Unit of atomic mass $\equiv (931{\cdot}478 \pm 0{\cdot}015)$ MeV,
$$1\ \mathrm{eV} \equiv (16{,}021{\cdot}0 \pm 0{\cdot}6) \times 10^{-16}\ \mathrm{erg}.$$

This list is based on the Report to the Commission on Nuclidic Masses and Related Atomic Constants, I.U.P.A.P., 24 June 1963, by E. R. Cohen, J. W. M. Du Mond.

RATIOS BETWEEN MEASUREMENT UNITS OF ENERGY AND OF MASS

Mega-electronvolt (MeV)	$4{\cdot}45 \times 10^{-20}$ kWh
	$1{\cdot}6 \times 10^{-13}$ J
	$1{\cdot}6 \times 10^{-6}$ erg
	$3{\cdot}83 \times 10^{-14}$ cal
	$18{\cdot}00 \times 10^{-28}$ gr_m
erg (erg)	10^{-7} J
	$2{\cdot}39 \times 10^{-8}$ cal
	$2{\cdot}78 \times 10^{-14}$ kWh
	$6{\cdot}24 \times 10^{5}$ MeV
	$0{\cdot}11 \times 10^{-20}$ gr_m
joule (J)	10^{7} erg
	$0{\cdot}23$ cal
	$0{\cdot}27 \times 10^{-6}$ kWh
	$0{\cdot}62 \times 10^{13}$ MeV
	$0{\cdot}11 \times 10^{-13}$ gr_m
calorie (cal)	$4{\cdot}18 \times 10^{7}$ erg
	$4{\cdot}10$ J
	$1{\cdot}16 \times 10^{-4}$ kWh
	$2{\cdot}6 \times 10^{13}$ MeV
	$4{\cdot}6 \times 10^{-14}$ gr_m
kilowatthour (kWh)	$3{\cdot}6 \times 10^{13}$ erg
	$3{\cdot}6 \times 10^{6}$ J
	$8{\cdot}6 \times 10^{5}$ cal
	$2{\cdot}25 \times 10^{19}$ MeV
	4×10^{-8} gr_m
gram-mass (gr_m)	25×10^{6} kWh
	$5{\cdot}6 \times 10^{26}$ MeV
	$2{\cdot}1 \times 10^{13}$ cal
	9×10^{13} J
	9×10^{20} erg

List of the multiplying factors of the basic units for obtaining multiples and submultiples. (The symbols of the factors for multiples are printed in capital letters, those for submultiples in small letters with the exception of k for kilo.)

Name	Ratio to the basic unit	Symbol
pico	10^{-12} (0·000000000001)	p
nano	10^{-9} (0·000000001)	n
micro	10^{-6} (0·000001)	μ
milli	10^{-3} (0·001)	m
kilo	10^{3} (1,000)	k
Mega	10^{6} (1,000,000)	M
Giga	10^{9} (1,000,000,000)	G
Tera	10^{12} (1,000,000,000,000)	T

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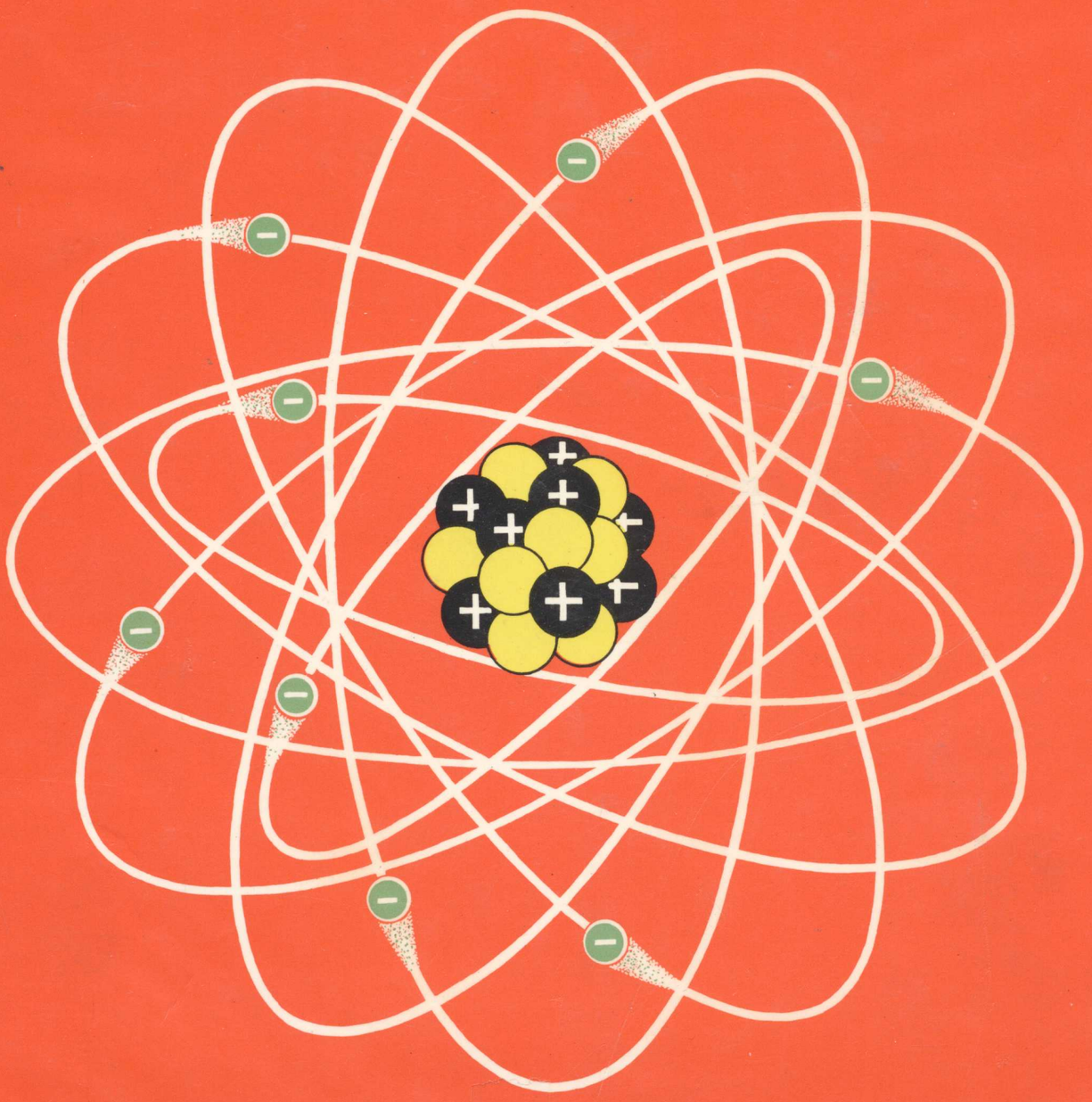
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